

Understanding The Drivers of Industry 4.0 Technologies to Enhance Supply Chain Sustainability: Insights From the Agri-Food Industry

Guoqing Zhao^{1*}, Xiaoning Chen², Paul Jones¹, Shaofeng Liu², Carmen Lopez³, Leonardo
Leoni⁴, Denis Dennehy¹

¹School of Management, Swansea University, Swansea, UK

²Plymouth Business School, University of Plymouth, Plymouth, UK

³Southampton Business School, University of Southampton, Southampton, UK

⁴Department of Industrial Engineering, University of Florence, Italy

*Corresponding author: guoqing.zhao@swansea.ac.uk

Understanding The Drivers of Industry 4.0 Technologies to Enhance Supply Chain Sustainability: Insights From the Agri-Food Industry

Abstract

The sustainability of agri-food supply chains (AFSC) has been under significant threat from regional and global events (e.g., conflict, natural and human-made disasters, climate crises). In response to these sustained threats, the AFSC industry is seeking digital solutions using Industry 4.0 (I4.0) technologies to enhance the resilience and efficiency of supply chains. Despite the transformational potential of I4.0, there is limited understanding to why its adoption remains stubbornly low in the agri-food industry. To address this gap, this study draws on middle-range theory (MRT) and builds on nine selected case studies located in China, each of whom have invested in I4.0 technologies to improve the sustainability of their AFSC. Data is examined using thematic analysis, the fuzzy analytic hierarchy process, total interpretive structural modelling, and fuzzy cross-impact matrix multiplication applied to classification. This study identifies several new drivers of I4.0 that are unique to the agri-food industry and how I4.0 can contribute to the environmental, economic, and social dimensions of AFSC sustainability. The results have implications for AFSC researchers and practitioners with an interest in supply chain sustainability.

Keywords: Industry 4.0, agri-food supply chains, fuzzy analytical hierarchy process, total interpretive structural modeling, fuzzy cross-impact matrix multiplication applied to classification analysis

1. Introduction

Agri-food supply chains (AFSCs) are inherently complex systems involving various stakeholders (e.g., suppliers, farmers, processors, wholesalers, distributors, and retailers) who engage in agriculture-related activities to move products across the chain from ‘farm to fork’ (De Carvalho et al. 2022; Zhao et al. 2024). In contrast to other food supply chains (e.g., tinned food), agri-food products are characterized by perishability, seasonality, and short life cycles, and specialized transportation and storage conditions are required to maintain product quality (Zissis et al. 2017).

AFSCs play a critical role in achieving the United Nations Sustainable Development Goal 2 (i.e., End hunger, achieve food security and improved nutrition and promote sustainable agriculture). Despite its importance, the sustainability of AFSCs itself is under threat from several regional and global challenges. For example, in line with the predicted growth in

population, urbanization, and increased consumption, agri-food production will need to increase 70% by 2050 (Spanaki et al., 2021). [At the same time, the environmental effects of the agri-food system could increase by 50% to 90% by 2050, reaching levels that are beyond the planetary boundaries that define a safe operating space for humanity \(Springmann et al., 2018\).](#) The environmental effects of the agri-food system include excessive use of agrichemicals to increase productivity which may contaminate water supplies and the agricultural sector contributes to 21% of global greenhouse gas emissions (SDWF, 2023).

[In this study, we draw on nine selected case studies located in China, each of which has invested in I4.0 technologies to improve the sustainability of their AFSC.](#) China provides a unique context for the purpose of this study for several reasons. Despite agricultural products with a cumulated value of almost 99 billion U.S. dollars being exported from China in 2023, it has become the largest importer of agricultural products in the world (Statista, 2024a). The reasoning for this over reliance on imports is that the Chinese agricultural industry can no longer meet the increase in demand due to a scarcity of arable land and therefore is less competitive in a trade-open environment (Statista, 2024b).

I4.0 have the capability to enhance the sustainability of AFSCs by improving stakeholder collaboration, enhancing information sharing, augmenting decision making and creating value (Gebhardt et al., 2022; Huber et al., 2022). Recent studies (e.g., Chatterjee et al., 2023; Chou & Shao., 2023; Margherita & Braccini, 2023) have explored various aspects of I4.0 and supply chain sustainability such as the mediating role of factors between I4.0 and supply chain practices, sustainable supply chains and a circular economy, and evaluation of sustainability performance. Despite the important contributions of these studies, a holistic understanding of the drivers of I4.0 applications and their impact on the three pillars of sustainable performance (i.e., environmental, social and economic) is lacking (Srhir et al., 2023). There is also a scarcity of studies that have used a range of techniques to analyse the drivers of I4.0 technology deployment to achieve AFSC sustainability (Agrawal et al., 2022; Taddei et al., 2022; Yadav et al., 2022).

At this point, we see another knowledge deficient related to I4.0 and its effects on AFSCs. [Previous studies focused on the role of I4.0 and supply chain sustainability are largely in the context of the manufacturing industry and therefore understanding of its adoption and implementation is well developed \(Yadav et al., 2022\).](#) As the agri-food industry is distinct

from manufacturing industry, its challenges to adopting I4.0 and understanding its contributions to AFSC sustainability is less well understood (Birkel and Muller, 2021; Tseng et al., 2018). Therefore, identifying and prioritizing the drivers to better understand the potential of I4.0 technologies in AFSC is warranted as several literature reviews (e.g., Agrawal et al., 2022; Taddei et al., 2022; Yadav et al., 2022; Srhir et al., 2023) highlight the need to employ different analytical techniques to gain a deeper understanding of the enablers and drivers of I4.0 technology deployment to achieve sustainable supply chains. In the context of this study, the results of the literature review reveal that only six of the 56 primary papers focus on analyzing the drivers, enablers, success factors, decision frameworks, or facilitators to achieve sustainable supply chain, green supply chain, circular economy, or sustainable development. This study addresses this gap by conducting an empirical study of I4.0 technology deployment to achieve AFSC sustainability and by adopting multiple analytical techniques to investigate the issues.

Against this background, this study aims to answer three interrelated research questions (RQ).

RQ 1. What drivers facilitate the adoption of I4.0 in AFSC?

RQ 2. How are these drivers prioritised?

RQ 3. Which of these drivers should AFSC practitioners focus?

To answer these questions, we conducted three phases of research: first, semi-structured interviews were conducted with AFSC practitioners in China to identify the drivers that facilitate the adoption of I4.0 (RQ1). Next, the fuzzy analytic hierarchy process (AHP) was used to rank the drivers and evaluate their weightings in relation to the three pillars of AFSC sustainability (RQ2). Then, interpretive structural modelling (TISM) and fuzzy cross-impact matrix multiplication applied to classification (MICMAC) analysis was conducted to identify key drivers by building a hierarchical framework and categorizing the drivers based on their driving and dependence power (RQ3).

This study advances understanding about the deployment of I4.0 technology to achieve AFSC sustainability and suggests adoption routes for AFSC practitioners. Further, by identifying two key drivers of I4.0 adoption not mentioned in previous AFSC studies, and aggregating several agri-food industry-specific drivers rarely mentioned in previous studies the study provides a holistic understanding to this important phenomenon that impacts all societies.

The remainder of this paper is structured as follows. First, background literature to middle-range theory (MRT), and a systematic literature review on the applications of I4.0 in the context of AFSCs is provided. Next, the data collection and data analysis methods are explained. Then, the analysis and findings are presented. Followed by a discussion, implications, and opportunities for future research. The paper ends with a conclusion.

2. Literature review

2.1 Middle-range theory (MRT)

Theories are widely used to explore the relationship between I4.0 and sustainability issues. For example, Abdul-Hamid et al. (2021) investigate drivers of I4.0 in a circular economy by deploying ecological modernization theory (EMT), whereas EMT posits that advanced technologies can improve the value added in both the economic and environmental dimensions. Karmaker et al. (2023) explore the impact of I4.0 on sustainable supply chain performance through resource-based view (RBV), whereas the theory assumes that firms gain competitive advantage by controlling scarce and valuable resources. Other theories that are frequently used to understand supply chain sustainability under I4.0 context, including institutional theory, dynamic capabilities (DC), innovation diffusion theory, social network theory, and information processing theory. These theories are useful to explore a wide range of phenomena by defining relationships and concepts, but they are criticized by scholars that can only be used to focus on phenomenon operationalized at a high level of abstraction with little functional context or specificity (Stank et al. 2017). This resulted a weak understanding of why and when the investigated phenomenon occurs.

MRT differs from other theories by restricting their explanation of causal connections to a subset of phenomena operating within a given context (Pellathy et al. 2018). It focuses on understanding how and why constructs are related, and under what conditions, therefore helping to consolidate knowledge within a particular domain. [For example, Burns et al. \(2023\) develop a MRT to understand motives and controls for insider computer abuse, and Hassan and Lowry \(2015\) call for using MRT in more information systems research.](#) There are three essential elements to conduct formal MRT: (1) conducting research within a specified domain of knowledge; (2) building or establishing relationships based on existing findings within that domain; and (3) concentrating on causal mechanisms and the contexts in which they produce outcomes (Pawson and Tilley. 1997). MRT is suitable for this study because of several reasons.

First, MRT aims to extend knowledge within a mature discipline, which is particularly suitable for this study that the topic has been explored by various scholars (Bhatia and Kumar. 2022; Lu et al. 2022; Mastrocinque et al. 2022). Second, we aim to understand of I4.0 deployment to achieve AFSC sustainability by exploring various drivers. In this case, drivers can be considered as enabling environment and deployment of I4.0 technology can be considered as mechanism to jointly achieve AFSC sustainability, which fulfil the MRT framework of mechanisms + context = outcomes (Pawson and Tilley, 1997). Third, the accumulated knowledge in I4.0 and supply chain sustainability can be leveraged to establish relationships between variables. To build a theoretical framework empowered by MRT, we first examining the accumulated knowledge of using I4.0 technologies to enhance supply chain sustainability. It aims to derive a research question from the phenomenon of interest (Craighead et al. 2024). For example, in this study, our research questions focus on identification and prioritization of drivers that facilitate the adoption of I4.0 in AFSC. Once derived research questions, we then contextualized our MRT to determine how to engage theory. There are three basic approaches available to choose: induction, deduction and abduction. An inductive approach is suitable because it examines meanings, processes, or contexts that are difficult to quantify. For example, this study aims to understand why and how drivers are related, and under what conditions that these drivers can be used to facilitate the adoption of I4.0 technologies. The situation makes it difficult to gain a deep understanding by employing a quantitative approach. We therefore firstly analyze rich qualitative data to reveal drivers facilitate the adoption of I4.0 technologies. Then, we employed two research techniques to further explore key findings to enhance theoretical and practical implications. Finally, we linked the mechanisms, contexts, and outcomes to formulate a MRT framework. The developed conceptual framework is shown in Figure 1.

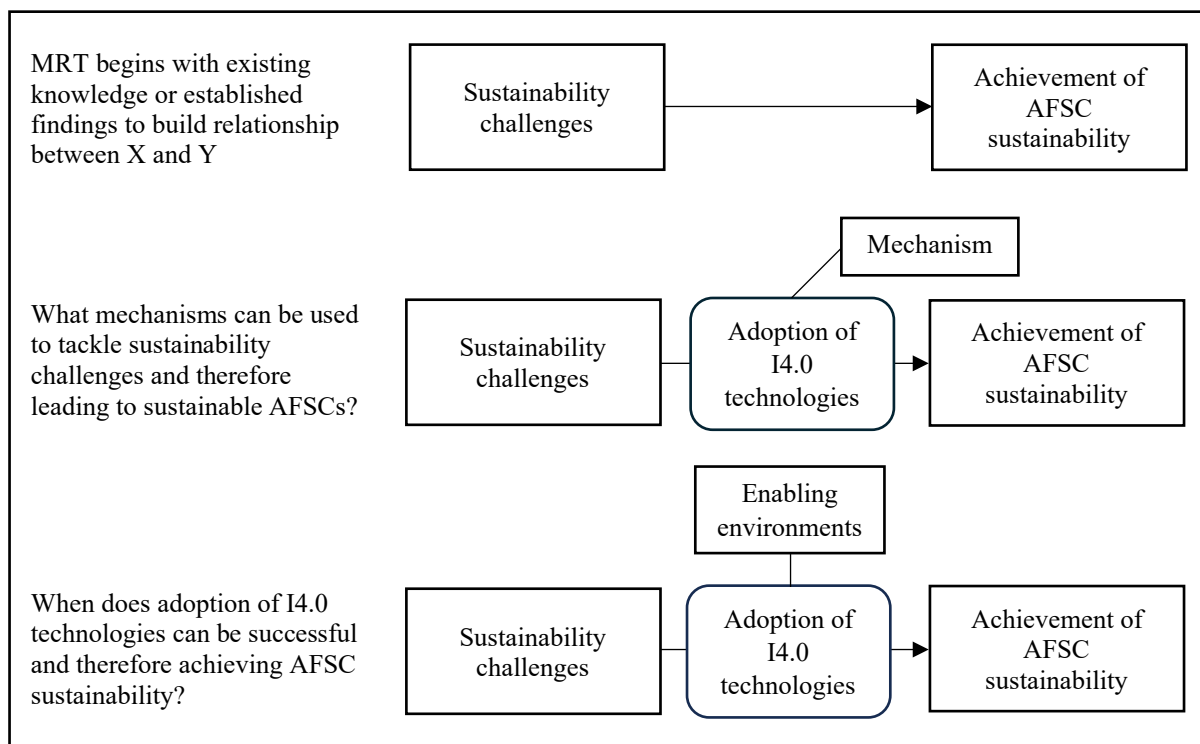


Figure 1 Conceptual framework

2.2 Application of I4.0 technologies in AFSC management

I4.0, representing the fourth industrial revolution, was originally proposed in 2011 to upgrade and reshape the manufacturing sector by integrating advanced information technologies (Lu et al., 2022). The aims are to maximize production efficiency to satisfy customized individual needs for products and services, enhance flexibility and connectivity, and minimize production costs by establishing smart, automated, integrated, and intelligent manufacturing processes (Zhang et al., 2021). Several I4.0 technologies have been widely discussed and applied, including facial recognition enabled by AI to enhance value in the travel and tourism industry (Gupta et al., 2023), IoT-based information systems for logistics 4.0 (Tang et al., 2023), and BDA powered by AI-machine learning (ML) smart city management (Alahakoon et al., 2023). Yin et al. (2018) concludes that I4.0 comprises seven technologies, whereas Tang and Veelenturf (2019) identify six. Zheng et al. (2021) propose that ten technologies should be I4.0 technologies: IoT, cyber-physical systems, BDA, cloud technology, AI, blockchain, simulation and modeling, augmented/virtual reality, automation and industrial robots, and additive manufacturing. The lists of I4.0 technologies in the literature lack consistency, perhaps for two reasons. First, scholars understand I4.0 design principles differently, resulting in diverse I4.0 technologies. For example, Qin et al., (2016) and Alguliyev et al., (2018) suggest six key characteristics of I4.0 technologies: decentralization, modularity, interoperability,

virtualization, real-time support, and service orientation. However, Aoun et al., (2021) consider only three characteristics: vertical networking of smart production systems, horizontal integration of global value chain networks, and through-life engineering across the entire value chain. Second, industries have unique characteristics, and therefore emphasize different technologies to accelerate their I4.0 adoption. For example, the logistics industry may focus on blockchain technology, the healthcare industry may concentrate on BDA, and the maritime industry may strengthen automation through robotics. Based on a critical review of papers published in reputable journals and consideration of I4.0 characteristics, our synthesis of existing works consists of eleven I4.0 technologies (see Table 1), adding drones to Zheng et al.'s (2021) list.

AFSCs are facing challenges such as food price volatility, quality and safety issues, food wastage and loss, and food fraud (Zhao et al., 2022). I4.0 technologies have been applied to alleviate or tackle these challenges. For example, self-driving robots have been utilized for automatic spraying of pesticides and crop harvesting (Javaid et al., 2022), ML algorithms have been used for crop and soil monitoring, and BDA has been applied to track and anticipate environmental impacts on agricultural outputs (Ranjha et al., 2022). IoT is widely used to monitor and control food processing equipment and can be utilized with AI to take corrective actions to avert machine breakdowns (Dadhaneeya et al., 2023). Pele et al. (2023) propose an IoT- and blockchain-based framework that can be applied to AFSC logistics. This promises several benefits, including reducing the number of middlemen and building trust at the intra-company level, creating transparency and reducing errors at the inter-company level, and reducing cost and delivery times at the customer level. Duong et al.'s (2020) summary of applications of robotics and autonomous systems (RAS) in AFSCs suggests that applications commonly integrate RAS into AFSCs to achieve food quality, safety, and waste reduction, and enhance supply chain efficiency and analysis. Based on a review of over 80 journal articles, Sharma et al. (2020) identify that ML has been adopted in four phases of AFSC management: pre-production (e.g., irrigation management and analysis of soil properties), production (e.g., disease detection and weather prediction), processing (e.g., demand and quality management), and distribution (e.g., transportation and retail management). I4.0 is a relatively new concept and encompasses many technologies. Each has unique features that allow its application in different phases of AFSCs including farming, processing, distribution, and retailing. For example, IoT, sensors, smartphones, and ML can be applied to the production phase for irrigation management (Kamienski et al., 2019), and 3D printing is characterized by layer-by-

layer material deposition directly from a pre-designed file. The technology can be applied at the food processing stage for customized food design and personalized food nutrition (Liu et al., 2017); IoT, blockchain, and sensors can be used in the distribution phase for traceability (Zhao et al., 2019); and BDA, smartphones, and cloud computing can be used in the retailing phase to predict consumer preferences (Erevelles et al., 2016). Evidence of how I4.0 applications are used in AFSCs are listed in Table 1, whereby three ticks (√√√) indicate strong evidence, one tick (√) indicates weak evidence, and no tick indicates no evidence.

Table 1. Use cases of I4.0 technologies in AFSCs

I4.0 technology	Use case in AFSCs				Description of applications
	Farming	Processing	Distribution	Retailing	
AM/3D printing		√√√			3D-printed meat, chocolates and snacks
AI/ML	√√√	√√√	√√√	√√√	Soil property analysis, irrigation management, weather prediction, quality and inventory management, consumer analysis
Augmented reality/virtual reality	√√√	√	√	√	Dietary assessment, food nutrition and traceability, retail food chain applications, education and training
Big data analytics	√	√	√	√√√	Waste minimization, reliable forecasting, better decision-making, improved knowledge and insights
Simulation and modeling	√√	√	√	√	Crop growth monitoring
Cyber-physical systems	√√√	√	√		Crop growth monitoring, soil moisture monitoring, weather monitoring
Blockchain	√	√	√√√	√	Traceability, food safety, transparency, eliminating food fraud
Cloud computing	√√√	√	√√	√	Precision agriculture, environment monitoring, irrigation systems, traceability
Drones	√√√			√	Environment monitoring, thermal imaging for watering, weed management, delivery services
IoT	√√√	√√√	√√√	√√√	Traceability, data visualization, real-time support
Robotics	√√√	√√√	√	√√√	Seed mapping, micro spraying, animal detection,

	environmental conditions monitoring
Citation sources	Porter, 2015; Dankar et al. 2018; Antonucci et al. 2019; Belaud et al. 2019; Zhao et al. 2019; Ren et al. 2020; Sharma et al. 2020; Huang et al. 2021; Chai et al. 2022; Dora et al. 2022; Mahdad et al. 2022; Petit et al. 2022; Rejeb et al. 2022a; 2022b)

2.3 I4.0 technologies and supply chain sustainability

Previous studies examined the impact I4.0 on supply chain digitalization and performance analysis, utilization of I4.0 to improve supply chain productivity, and barriers to its deployment to achieve supply chain sustainability (Bag et al., 2021; Agrawal et al., 2022; Gebhardt et al., 2022). In research on the relationship between I4.0 and sustainability, special attention is given to I4.0's contributions to the three pillars of sustainability. Some papers take a general perspective, while others concentrate on specific factors. For example, Ghobakhloo et al., (2020) indicate 16 opportunities provided by I4.0 for sustainability, including some frequently mentioned by other scholars, such as greenhouse gas emissions reduction, energy and resource sustainability, human resource development, and social welfare enhancement. According to Naseem and Yang (2021), I4.0 empowers product planning and scheduling, storage, and distribution, purchasing and sourcing, and production processes, thereby enhancing the environmental, social, and economic sustainability of supply chains. The topic of supply chain digitalization and performance analysis focuses on I4.0 technology implementation and its implications for supply chain performance. For example, Sengupta et al.'s (2022) case study illustrates how blockchain technology improves supply chain resilience and generates income opportunities for those in poor fishing communities. Mesquita et al. (2022) highlight the integration of lean and I4.0 to achieve environmental sustainability. Another important topic closely linked with both I4.0 and supply chain productivity. Amongst many conceptual and empirical studies relevant to this topic are Fracapane et al.'s (2022) examination of the role of autonomous robotics in increasing productivity and flexibility of production networks and Enrique et al.'s (2023) study of arrangements of I4.0 technologies to achieve different purposes (e.g., manufacturing flexibility, process quality, and productivity). Papers on challenges or barriers to I4.0 deployment to achieve supply chain sustainability focus on identifying, prioritizing, linking, and clustering them using various analytical and modeling techniques. Finally, subtopics relevant to I4.0 and the circular economy include theoretical models for implementing of I4.0 in the context of the circular economy and case studies exploring the intersections between the circular economy and I4.0 (Awan et al., 2021; Chauhan et al., 2021).

This area is fragmented because supply chain sustainability is a broad term comprising many elements (environmental, social, and economic), and can be achieved through various capabilities, such as collaboration, coordination, and supply chain integration (Piccarozzi et al., 2022). Although extant literature explores a range of topics relating to I4.0 technologies and supply chain sustainability, further investigation of the drivers of I4.0 deployment will advance understanding of their integration into sustainable supply chains (Taddei et al., 2022; Srhir et al., 2023).

3. Systematic literature review of the drivers of I4.0 technology deployment to achieve supply chain sustainability

Consistent with previous reviews of the literature on achieving supply chain sustainability using I4.0 technologies (Birkel & Muller, 2021; Piccarozzi et al., 2022; Srhir et al., 2023), a search string of 18 keywords was used to identify the drivers of I4.0 technology deployment (see Figure 2).

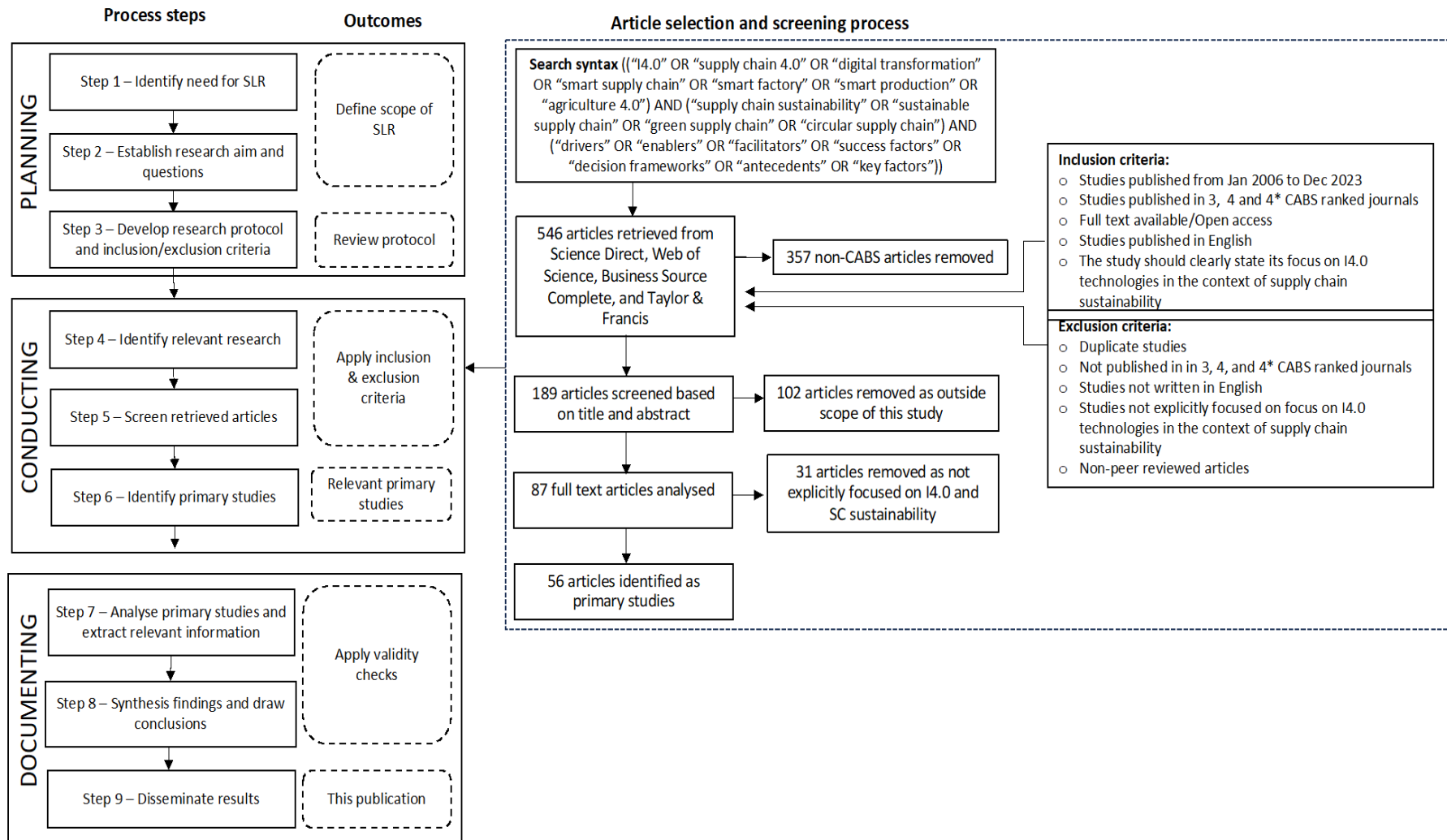


Figure 2. SLR process

The characteristics (i.e., journal outlet, methodology, topic of focus, and industry context) of the 56 primary papers are listed in Table 2.

Table 2. Characteristics of the 56 primary papers

Journal Outlet	<ul style="list-style-type: none"> • Business Strategy and the Environment (n=15) • Production Planning & Control (n=11) • Technological Forecasting and Social Change (n=7) • IEEE Transactions on Engineering Management (n=6) • International Journal of Production Economics (n=5) • Computers in Industry (n=3) • Industrial Marketing Management (n=2) • Annals of Operations Research (n=2) • International Journal of Production Research (n=2) • Production and Operations Management (n=1) • Supply Chain Management: An International Journal (n=1) • Technovation (n=1)
Research methodology used	<ul style="list-style-type: none"> • Theoretical and conceptual papers (n=10) • Case studies/interviews (n=10) • Survey (n=12) • Modelling (n=9) • Literature reviews (n=15)
Topic of focus	<ul style="list-style-type: none"> • Analysis of drivers to achieve sustainable supply chain (n=6) • Proposed frameworks, strategies, and capabilities to use I4.0 technologies to achieve sustainable supply chain (n=16) • Use of I4.0 technologies to achieve sustainable supply chain/circular economy (n=15) • Frameworks to evaluate sustainable supply chain performance using I4.0 (n=10) • Mediating role of variables between I4.0 and sustainable supply chain practices (n=9)
Industry context	<ul style="list-style-type: none"> • Renewable energy (n=1) • Construction (n=1) • Electronics (n=1) • Manufacturing (n=15) • Automobile (n=5) • Maritime (n=1) • Smart (n=1) • Logistics (n=1) • Agri-food (n=3) • Not specified (n=27)

The systematic literature review identified many drivers that were reported in previous studies, as well as new drivers (highlighted in bold) that emerged from this phase of the study (see Table 3).

Table 3. The drivers of I4.0 technology deployment

Drivers identified by existing studies	Employment and jobs, social acceptability, governmental support for R&D, GHG emissions reduction, green policies on disposal, technology for disposal, improved productivity, operational cost reduction, faster transactions, efficient use of energy, water management, reduced waste and delays, food safety, good working environment, autonomous operations, collaboration and coordination between parties, resource allocation, real-time information tracking, real-time dynamic decision-making, increased service levels, reduced errors, optimized supply chain flows, top management support, continuous monitoring of emissions reductions, sustainable human resource management, smart budget allocation, promoting knowledge management in supply chains, reward policies and incentives for sustainability adoption, creation of smart networks, comprehensive data collection, imparting appropriate training and skills to employees, control and flexible orientation, overcoming operational challenges, transferring business models and processes, knowledge of circular supply chain, cross-functional collaboration, modular processes for simplification and standardization
Drivers identified in this study	Reducing work intensity , reducing labour headcount, reducing human exposure to pesticides , strengthening farmers' agri-tech skills training, improving work conditions, reducing carbon emissions, reducing groundwater pollution , reducing waste by controlling resource competition, enhancing the efficiency of water and fertilizer use , improving government subsidies for agricultural facilities, increasing product safety and farms' productivity, reducing labor costs, accelerating circular agriculture

4. Research methodology

We adopted a qualitative approach to analyze the drivers of I4.0 technology deployment to achieve AFSC sustainability. This approach promised several advantages. First, a qualitative approach provides an in-depth understanding of the phenomenon which would be difficult to gain from a quantitative study. Second, qualitative data can capture the diversity of environments or situations. In our study, we analyze various drivers, captured through qualitative interviews. Third, qualitative data can help to generate new ideas, concepts, and theories (Jogulu & Pansiri, 2011). We address criticism that qualitative data may be subject to credibility and reliability issues by employing multiple data analysis techniques, including thematic analysis, fuzzy AHP, TISM, and fuzzy MICMAC analysis (see Figure 3).

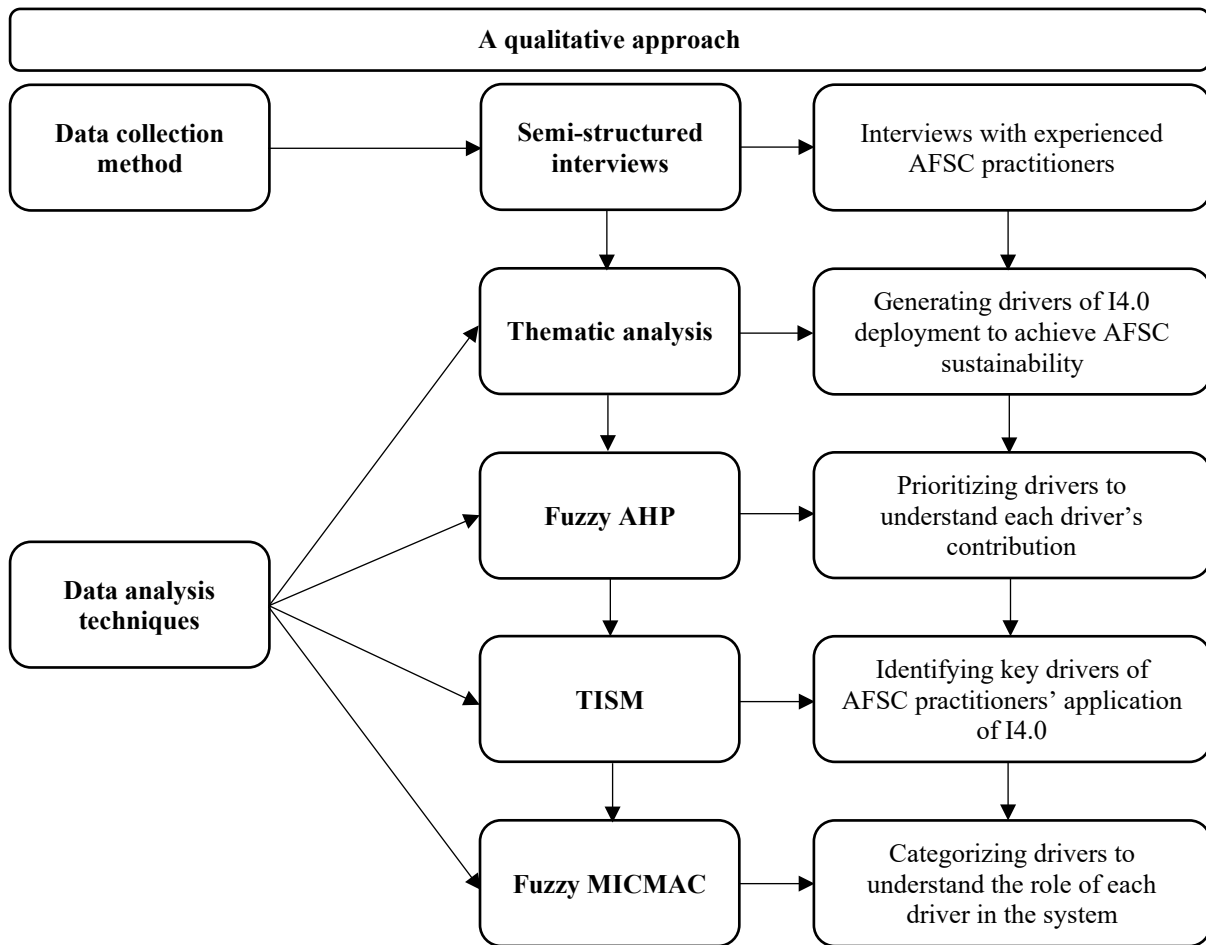


Figure 3. Research methodology adopted

4.1 Data collection method

Semi-structured interviews, simply defined as purposeful conversations (Burgess, 1984), are a widely used qualitative research method allowing researchers and participants to explore a pre-determined set of research questions (Saunders et al., 2009). We adopted this method for several reasons. First, our conversation with interviewees were guided by a pre-defined list of open-ended questions, providing a set of themes on which to focus, while also allowing us to probe interesting and relevant issues (Barriball & While, 1994). This critical advantage over structured and unstructured interviews enables elicitation of more valuable and complete information on the topic. Second, participants were provided with sufficient opportunities to speak freely during the interviews, even on sensitive topics, thereby helping to generate highly meaningful information and reveal novel aspects (McIntosh & Morse, 2015). For example, government subsidies may be one driver of farmers' use of advanced agricultural facilities, and this approach allowed us to discuss the amounts of subsidies they received from the

government. Finally, a high response rate was achieved by ensuring that participants were able to answer all the questions.

4.2 Data analysis techniques

Four complementary data analysis techniques (i.e., thematic analysis, fuzzy AHP, TISM, and fuzzy MICMAC analysis) were employed in this study. Each is presented in order of use in this study.

Thematic analysis: This technique was used to generate the drivers based on the data collected from the semi-structured interviews. Thematic analysis is an easily grasped, widely accepted, and foundational method for conducting qualitative analysis, used mainly to identify, describe, organize, and report themes found within a dataset (Braun & Clarke, 2006). It was adopted for several reasons. First, the results of thematic analysis are easily understood by members of the public with low educational levels, which suited our research context and would enable broad impacts on the agri-food industry. Furthermore, thematic analysis enables key features of a large dataset to be summarized (Nowell et al., 2017), and was thus suited to this study, which produced 130 pages of transcripts from 26 semi-structured interviews. Thematic analysis is also useful for generating insights into aspects and highlighting similarities and differences across diverse participants (King, 2004).

Fuzzy AHP: The results of our thematic analysis as inputs into fuzzy AHP. Our aims were to prioritize drivers and understand the contributions of I4.0 technologies to different dimensions of AFSC sustainability. AHP is a widely applied MCDM method for prioritizing alternatives hierarchically (Awasthi et al., 2018). We integrated fuzzy sets with AHP because this helps to tackle the imprecision of AHP while retaining its advantages (Liu et al., 2020). Other prioritization methods are available but could not be applied in this study owing to various limitations. For example, the interpretive ranking process (IRP) is an effective MCDM method used to rank a set of variables, but the process becomes difficult with more than 10 variables and the interpretive process is highly subjective (Mangla et al., 2018). Data envelopment analysis (DEA), a powerful mathematical model for ranking alternatives in multi-criteria decision analysis, is better suited for performance measurement activities (Mardani et al., 2017).

TISM: This technique was used to identify key drivers by constructing interrelationships between them, thereby helping to understand potential routes through which AFSC

practitioners might effectively deploy I4.0 technologies to achieve AFSC sustainability. TISM is an effective qualitative modeling method widely deployed to build hierarchical frameworks to illustrate interactions between variables (Sushil, 2012). It offered several advantages for this study. For example, TISM enables interpretation of links between two variables, which is lacking in ISM (Jena et al., 2017). The decision-making trial and evaluation laboratory (DEMATEL) can be used to identify cause-effect relationships between variables by building structural models, but it has limited applicability (Si et al., 2018), whereas TISM can be used in a range of areas. Finally, ANP is effective in revealing interdependencies between variables in a network-based system but, unlike TISM, it relies heavily on experts' judgments and experience (Zhao et al., 2020).

Fuzzy MICMAC: This technique was used to classify drivers and validate the TISM model based on each driver's driving and dependence power. We adopted this method for several reasons. We initially used (non-fuzzy) MICMAC analysis to categorize variables based on binary relationships. However, one drawback of MICMAC is that it does not evaluate the strength of relationships between two variables, thereby causing imprecision (Mota et al., 2021). Thus, fuzzy MICMAC analysis was applied to strengthen our sensitivity analysis. Furthermore, TISM and fuzzy MICMAC analysis have previously been combined to analyze issues relating to supply chain sustainability (Luthra & Mangla, 2018).

5. Empirical data collection

Data collection was conducted in Shandong, a province in China between November 2021 and March 2022. Shandong was suited to this study as its vegetable production has been ranked first among China's 34 provinces since 2015. In context more than 80 million tons of vegetables were produced in 2021 (Ministry of Agriculture and Rural Affairs, 2021). Purposive sampling (Creswell, 2014) was used to identify individuals with extensive experience related to the AFSC industry. This approach resulted in 26 qualified individuals agreeing (see Table 4) to participate in a semi-structured interview.

Table 4. Interviewee profile

Case study code	Sector	Job title	Years of experience
A	Vegetable planting and simple processing (tomatoes and Chinese cabbage)	Technical director	12
		Director	25
		Sales director	15
B	Pig farming	Technical manager	22
		Research and development director	24
		Director	26
C	Egg production and processing	Human resource manager	15
		Technical director	22
		Director	24
D	Vegetable production and processing (tomatoes and cucumbers)	Director	19
		Financial manager	22
		Technical director	15
E	Promoting agricultural technologies and training farmers	Chief researcher	32
		Researcher	21
		Director	25
F	Agricultural technology development	Professor in agricultural science	30
		Professor in agroecconomics	23
		Professor in agricultural engineering	27
G	Regional agricultural policy development	Deputy director	22
		Chief of agricultural machinery	12
		Deputy director	25
H	Canned vegetable production	Human resource manager	15
		Procurement manager	20
		Marketing manager	19
I	Providing cold chain service to consumers	Maintenance manager	15
		Marketing manager	18

All interviews were recorded with permission, using voice memos on iPhone 13, and many probing questions were asked to enable participants to clarify their answers. Each interview lasted between 75 and 120 minutes to give participants sufficient time to elaborate on their answers. 48 hours of digital recordings was collected.

6. Data analysis and findings

6.1 Identification of drivers through thematic analysis

The thematic analysis consisted of five steps (see Figure 4). The first step was verbatim transcription of all digital recordings, which produced four to six pages of transcript per recording. A total of 130 pages of transcripts were generated from the 26 interviews. Second,

each transcript was read several times to increase familiarity with the data before generating initial codes. Third, during the coding process, data relevant to drivers of I4.0 technology deployment to achieve AFSC sustainability were coded inductively. NVivo 13 was used to assist in the coding process by highlighting, tagging, and naming data extracts. Next, codes extracted from the coding process were organized into groups by considering their interrelationships, and these overarching themes were labelled. These themes were then organized into higher-level aggregate dimensions by considering links between themes, which were named using established constructs from the existing literature on supply chain sustainability (Martins & Pato, 2019). Next, we refined the codes and themes by checking for links between codes, themes, and different levels of themes. During this process, an iterative approach was adopted, moving back and forth between relevant theory and data. Finally, we used King and Horrocks’s (2010) framework to organize the empirical evidence into first-order codes, second-order themes, and aggregate dimensions. Table 5 presents a sample of the empirical evidence on drivers of AFSC sustainability in the I4.0 context.

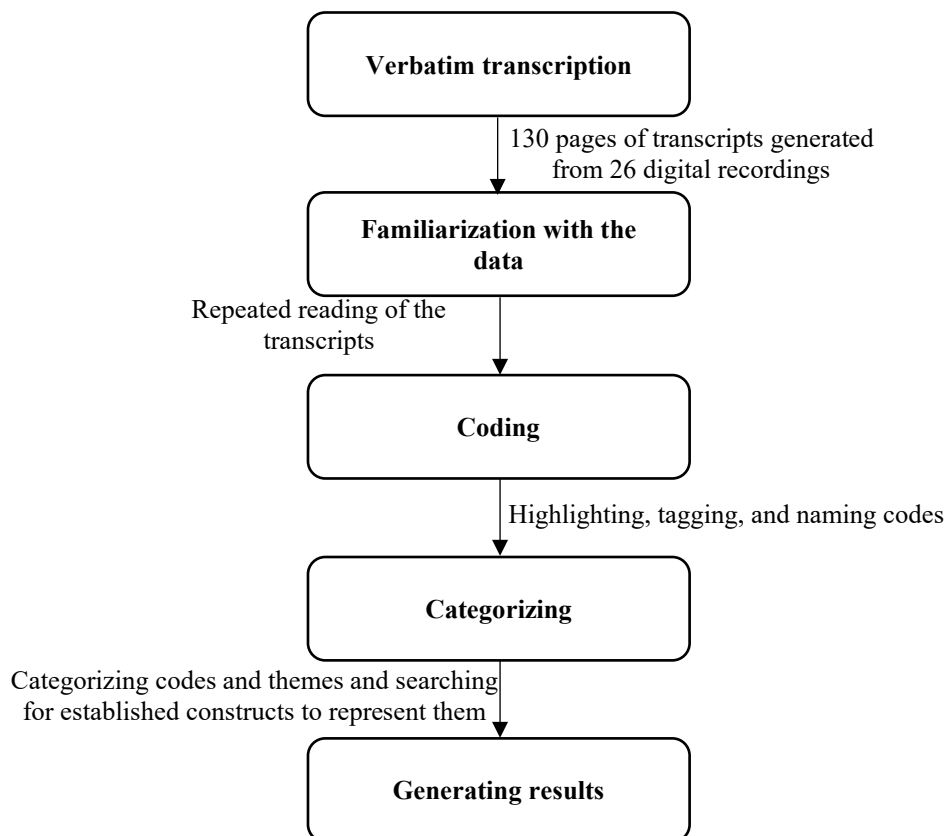


Figure 4. The thematic analysis process

The results of the thematic analysis pinpointed 13 drivers of I4.0 technology deployment to achieve AFSC sustainability. For example, from a social perspective, AFSC practitioners

deploy I4.0 technologies to assist in reducing work intensity, labor headcount, and human exposure to pesticides, strengthening farmers' agri-tech skills training, and improving working conditions. From an environmental perspective, deploying I4.0 technologies in AFSCs has positive effects in reducing carbon emissions and groundwater pollution, and reducing waste by controlling resource competition. From an economic perspective, the drivers identified are enhancing the efficiency of water and fertilizer use, acquiring government subsidies for agricultural facilities, improving product safety and farms' productivity, reducing labor costs, and accelerating circular agriculture.

Table 5. Empirical evidence revealing drivers

First-order codes	Second-order themes/drivers	Support from participants																				Aggregate dimensions							
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T		U	V	W	X	Y	Z	
“The country proposed to reduce operations such as reducing work employees’ work intensity.”	Reducing work intensity	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	Social	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
“...manpower consumption, so the work environment may be better.”	Reducing labour headcount	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
“The application of a water-fertilizer integration system is an advantage for our employees’ health.”	Reducing human exposure to pesticides	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
“Agricultural department is launching large-scale training for farmers to improve farmers’ knowledge.”	Strengthening farmers’ agri-tech skills training	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
“By deploying technologies such as automatic tractors...the working conditions have been improved.”	Improving working conditions	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√		√
“China’s energy-saving greenhouses are relatively good in terms of carbon emissions.”	Reducing carbon emissions	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
“The fertilizer will cause some harm to the environment through infiltration or volatilization.”	Reducing groundwater pollution	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
“If there are better agricultural facilities, there will be no need for heating.”	Reducing waste by controlling resource competition	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	
		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

“The application of a water-fertilizer integration system can help us to achieve more than 70% water saving.”	Enhancing the efficiency of water and fertilizer use	√ √	Economic
“The local government has subsidies for large-scale agriculture, which applies advanced agricultural technologies.”	Government subsidies for agricultural facilities	√ √	
“For example, we have a traceability system to ensure our product’s safety.”	Increasing product safety and farms’ productivity	√ √	
“As workers’ proficiency increases, our labor costs will gradually decrease.”	Reducing labor costs	√ √	
“They will recycle and do something to improve the soil.”	Accelerating circular agriculture	√ √	

Note: √ denotes weak evidence, √√√ denotes strong evidence

6.2 Prioritization of drivers using fuzzy AHP

Fuzzy AHP was used to prioritize the identified drivers to gain a better understanding of the management of I4.0 technologies to achieve AFSC sustainability. This consisted of five steps.

Step I: Defining and structuring the objective. One of our research objectives was to rank the drivers to understand each driver's contribution to AFSC sustainability in relation to applying I4.0 technologies. This objective was decomposed into a hierarchical structure, with the objective in the top level, followed by categories of drivers in the middle level (e.g., social, environmental, economic) and the drivers of each category in the bottom level.

Step II: Constructing a fuzzy judgment matrix \tilde{E} . Fuzzy judgment matrix \tilde{E} is a pairwise comparison matrix obtained by pairwise comparison of categories of drivers and the drivers in each. Appendix 1 shows the linguistic scales used to conduct pairwise comparisons. In this study, we produced five fuzzy judgment matrices because we sought to understand the relative importance of drivers in each category, the categories of drivers, and the global ranking of drivers.

$$\tilde{E} = \begin{bmatrix} \tilde{1} & \tilde{E}_{12} & \dots & \tilde{E}_{1n} \\ \tilde{E}_{21} & \tilde{1} & \dots & \tilde{E}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{E}_{n1} & \tilde{E}_{n2} & \dots & \tilde{1} \end{bmatrix} = \begin{bmatrix} \tilde{1} & \tilde{E}_{12} & \dots & \tilde{E}_{1n} \\ \tilde{E}_{12}^{-1} & \tilde{1} & \dots & \tilde{E}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{E}_{1n}^{-1} & \tilde{E}_{2n}^{-1} & \dots & \tilde{1} \end{bmatrix},$$

where

$$\begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}, \text{ criterion } i \text{ is relatively more important than criterion } j, \\ \tilde{1}, i = j, \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}, \text{ criterion } i \text{ is relatively less important than criterion } j \end{cases}$$

Step III: Calculating the fuzzy weights of each criterion. We followed Buckley's (1985) method to calculate the fuzzy weights of each criterion. In the following, \tilde{E}_{ij} is the fuzzy comparison value of criterion i to criterion j , \tilde{r}_i is the geometric mean of the fuzzy comparison value of criterion i to each criterion, and \tilde{w}_i is the fuzzy weight of the i th criterion.

$$\tilde{r}_i = [\tilde{E}_{i1} \otimes \tilde{E}_{i2} \otimes \tilde{E}_{i3} \dots \otimes \tilde{E}_{in}]^{1/n}, \forall i = 1, 2, 3, \dots, n$$

$$\tilde{w}_i = \frac{\tilde{r}_i}{\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \dots \oplus \tilde{r}_n},$$

Step IV: Hierarchical layer sequencing. The final fuzzy weight of each alternative was calculated through hierarchical sequencing:

$$\tilde{U}_i = \sum_{j=1}^n \tilde{w}_j \cdot \tilde{r}_{ij}$$

where \tilde{r}_{ij} is the fuzzy weight value of the j th criterion to the i th driver. \tilde{u}_i can be indicated by a triangular fuzzy number, $\tilde{U}_i = (l, m, u)$.

Step V: Ranking drivers. The final fuzzy weight values of drivers are represented in terms of fuzzy numbers. Thus, we followed Lee and Li's (1988) method to defuzzify and rank the fuzzy numbers.

The fuzzy AHP analysis reveals the contributions of Industry 4.0 technology deployment to achieving AFSC sustainability. The rankings of categories of drivers, the drivers in each category, and the global rankings of the specific drivers are shown in Table 6. The economic category is ranked first among the three categories of drivers, with a relative weighting of 0.5784. This means that AFSC practitioners are most concerned about the economic benefits of deploying I4.0 technologies, for several reasons. First, the cost of intelligent agricultural technical equipment is too high because applications of I4.0 technologies have just begun and production of this kind of equipment has not yet reached scale. For example, a water and fertilizer integration system will be expensive when integrated with customized automatic controls, PH value detection, and wireless mobile controls. Second, most AFSC practitioners work in small and medium-sized enterprises (SMEs) and are reluctant to apply these technologies unless they guarantee significant income increases. As one interviewee stated: *"intelligent agricultural equipment can only be applied by a farmer who has more than 200 or 300 acres of farmland, because the increased profits can cover the cost of this equipment"*. There are five drivers in this category: enhancing the efficiency of water and fertilizer is ranked first, followed by improving product safety and farms' productivity, reducing labor costs, accelerating circular agriculture, and acquiring government subsidies for agricultural facilities. For example, from the perspective of saving water, applying a water and fertilizer integration system and a drip irrigation system may reduce water use by more than 70%.

The environmental category of drivers is second in the priority list, with a relative weighting of 0.2942. The Chinese government's science and technology-supported action plan is to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (Ministry of Science and Technology, 2022). Therefore, technologies such as advanced sensors, intelligent

greenhouses, IoT, and remote controls should be used to monitor and reduce carbon emissions. For example, light, humidity, carbon dioxide, acidity, and irrigation monitoring sensors are applied in intelligent greenhouses to manage crops precisely. One interviewee stated: *“In the intelligent greenhouses, the heat flow can be controlled and used effectively. For example, if the ground temperature reaches above 12 degrees, we can grow warm-loving crops, and if the temperatures are between 6 and 8 degrees, we can grow cold-resistant crops”*. There are three drivers in this category. Reducing carbon emissions, reducing groundwater pollution, and reducing waste by controlling resource competition are ranked first, second, and third, respectively.

Finally, the social category of drivers is ranked in last place among the three categories. We assume that this category of drivers has received least attention owing to the Chinese hierarchical cultural value orientation. In this cultural environment, people view competition as good, and are required to obey the expectations of those in higher-status roles (Schwartz, 2006). For example, the 996 working hour system implemented by some companies in China requires employees to work from 9am to 9pm, six days per week. Under the 13th Five-Year Plan, the Chinese government proposed several tasks relating to agriculture, including increasing the informatization of agricultural equipment, improving agricultural support and protection systems, and enhancing the safety of agricultural products. Thus, I4.0 technologies, such as intelligent greenhouses, advanced sensors, and IoT, are applied to reduce work intensity and improve working conditions. However, blockchain technology and automatic tractors are not widely deployed for several reasons. First, Chinese farmers are aging, with the majority aged between 45 and 55, and are relatively unwilling to learn new knowledge: *“Farmers are relatively high in age level and relatively low in knowledge structure. Therefore, both model application and equipment maintenance are relatively lacking”*. Second, no standardized model can be used to apply these technologies because soil and weather conditions vary in different areas. Third, applying these technologies will significantly increase the costs of terminal logistics, particularly for blockchain technology applications. There are five drivers in this category: reducing work intensity is ranked first with a relative weighting of 0.4331, reducing human exposure to pesticides is ranked last with a relative weighting of 0.0576, and reducing labor headcount, improving work conditions, and strengthening farmers’ agri-tech skills training are ranked from second to fourth. As one interviewee stated: *“Local governments have provided training for new farmers, part of which includes information technology courses (e.g., technical equipment, IoT, blockchain, organizational models, and application models)”*.

Table 6. Ranking of drivers

Category of drivers	Relative weighting	Relative rank	Specific drivers	Relative weighting	Relative rank	Global weighting	Global rank
Economic	0.5784	1	Enhancing the efficiency of water and fertilizer use	0.4607	1	0.1998	1
			Government subsidies for agricultural facilities	0.0534	5	0.0194	12
			Improving product safety and farms' productivity	0.2321	2	0.1377	2
			Reducing labor costs	0.1773	3	0.1225	3
			Accelerating circular agriculture	0.0765	4	0.0183	13
Environmental	0.2924	2	Reducing carbon emissions	0.6688	1	0.0933	6
			Reducing groundwater pollution	0.2276	2	0.0645	7
			Reducing waste by controlling resource competition	0.1036	3	0.0389	9
Social	0.1292	3	Reducing work intensity	0.4331	1	0.1178	4
			Reducing labor headcount	0.2837	2	0.0966	5
			Reducing human exposure to pesticides	0.0576	5	0.0208	11
			Strengthening farmers' agri-tech skills training	0.0730	4	0.0287	10
			Improving working conditions	0.1526	3	0.0418	8

6.3 Generation of key drivers through TISM

Simply understanding the contributions of I4.0 technology deployment to AFSC sustainability is insufficient, as more than 80% of businesses in AFSCs are SMEs, so most AFSC practitioners lack the resources necessary to implement these technologies. The focus must therefore be on key resources, drivers, and enablers to initiate I4.0. Thus, we used TISM to identify the key drivers by constructing a hierarchical model, implementing a nine-step process.

Step I: Identification and definition of drivers. This step involved identifying and defining the drivers to be modeled. The 13 drivers identified through the thematic analysis were used as inputs into the TISM process.

Step II: Determination of contextual relationships. Our research objective was to identify key drivers to provide practical guidance to AFSC practitioners seeking to initiate I4.0. To fulfill this objective, a contextual relationship between two drivers was defined as “Driver A will enhance or enable Driver B.”

Step III: Interpretation of relationships. Two professors in operations management who had been collaborating with the agri-food industry for more than 20 years were involved in interpreting relationships between pairs of drivers. Their opinions were initially captured to determine whether “Driver A will enhance or enable Driver B”. If their answer was “yes”, a follow-up question was asked: “In what way will Driver A enhance or enable Driver B.” Capturing the experts’ opinions, enabled us to obtain in-depth knowledge of relationships between drivers.

Step IV: Interpretive logic of pair-wise comparison. We conducted pair-wise comparisons of the identified 13 drivers to obtain an interpretive logic-knowledge base. Each driver was individually compared with all the other drivers. The two professors’ opinions were captured to rate relationships between two drivers by coding them as “Y” for yes and “N” for no. Further interpretation was required if the relationship between two drivers was “yes”. The knowledge base for this study consisted of $n \times (n-1) = 13 \times (13-1) = 156$ rows, where n represents the number of drivers.

Step V: Reachability matrix and transitivity test. The initial reachability matrix was obtained by transforming “Y” codes in the knowledge base into “1” and “N” codes into “0”. We then transformed the initial reachability matrix into a final reachability matrix by conducting a transitivity test: if driver A relates to driver B, and driver B relates to driver C, then driver A necessarily relates to driver C. The initial and final reachability matrices are shown in Appendix 2.

Step VI: Level determination by partitioning the reachability matrix. This step was performed to determine the level of each driver in the TISM model by obtaining each driver’s reachability

and antecedent sets in the final reachability matrix. The reachability set for a particular driver consists of the driver itself and other drivers that it will enhance or enable, whereas a driver's antecedent set consists of the driver itself and other drivers that will enhance or enable it. The intersection set of each driver consists of common elements between the reachability and antecedent sets. If the elements in the reachability and intersection sets are the same, the driver is placed in the top level of the TISM model. The level partitioning process was performed until the level of each driver had been determined (see Appendix 3).

Step VII: Digraph development. We developed a digraph by allocating the drivers to their respective levels and drawing direct links according to the relationships shown in the final reachability matrix. Only important transitive links were retained following discussion with the two professors.

Step VIII: Interpretive matrix. A binary interpretive matrix was developed by translating all interactions in the digraph into 1 in the respective cell. The appropriate interpretation was selected from the interpretive logic-knowledge base to interpret relationships between pairs of drivers.

Step IX: TISM model of drivers. A TISM model of the drivers was developed (see Figure 5) by allocating the drivers to different layers of the framework, linking them with solid and dotted lines, and interpreting each link.

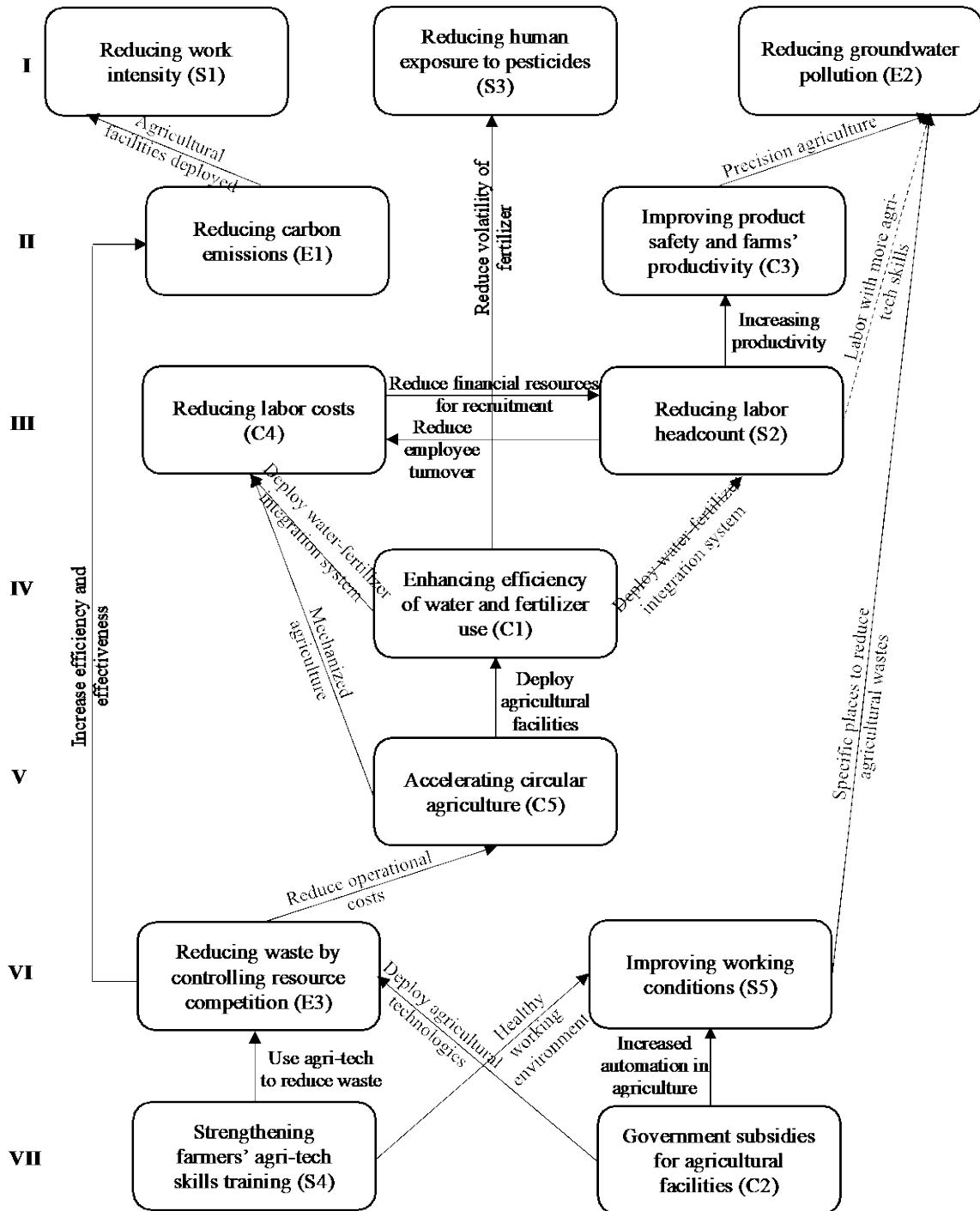


Figure 5. TISM model of drivers

The TISM analysis of drivers resulted in a seven-level hierarchical model. Strengthening farmers' agri-tech skills training (S4) and government subsidies for agricultural facilities (C2) are located at level VII of the TISM hierarchy, reducing work intensity (S1), reducing human exposure to pesticides (S3), and reducing groundwater pollution (E2) are at level I, and the other drivers are spread from levels II to VI. Drivers located at lower levels of the model can

enable more other drivers of the system, whereas those occupying higher levels of the model require more other drivers to achieve them. The analysis reveals two key drivers of the system: strengthening farmers' agri-tech skills training (S4) and government subsidies for agricultural facilities (C2). One interviewee stated: *"The local government spends more than ¥6 million per year to support agricultural technology, smart greenhouses, and other professional training. Furthermore, government subsidies are provided to exemplary agricultural enterprises because they act as links between farmers and agricultural research institutes and have a strong willingness to apply I4.0 technologies"*. Applications of I4.0 technologies in agriculture, such as IoT, water and fertilizer integration systems, advanced sensors, and smart greenhouses, have positive effects in reducing water and agrichemical use, and enhancing mechanized and automatized agriculture, thereby reducing waste (E3), improving working conditions (S5), and accelerating circular agriculture (C5). Specifically, a water and fertilizer integration system may significantly increase the efficiency of water and fertilizer use (C1). As one interviewee stated: *"The application of a water and fertilizer integration system can achieve more than 70% of water saving, which is critical for North China because they generally lack water"*. Other benefits achievable by deploying I4.0 technologies include reducing labor costs (C4), reducing labor headcount (S2), reducing carbon emissions (E1), improving product safety and farms' productivity (C3), reducing work intensity (S1), reducing human exposure to pesticides (S3), and reducing groundwater pollution (E2).

6.4 Categorization of drivers using fuzzy MICMAC analysis

We used fuzzy MICMAC analysis to critically analyze the scope of each driver by considering its driving and dependence power (Bhosale & Kant, 2016). Two primary considerations led us to adopt this method. First, AFSC practitioners must understand the scope of each driver when they are implementing I4.0 technologies to achieve AFSC sustainability. Adopting some drivers may achieve synergies, or they may conflict with other drivers, thereby reducing effective achievement of AFSC sustainability. Second, fuzzy MICMAC analysis was implemented as a complement to TISM because the latter rarely considers the strength of relationships between pairs of drivers. For example, relationships between two drivers were coded as "0" or "1" during the TISM implementation, with "0" representing no relationship, and "1" representing a relationship between the two drivers. However, other aspects of relationships need to be considered, as some relationships may be strong, some very strong, and some weak (Zhao et al., 2020). Our fuzzy MICMAC analysis was conducted in three steps.

Step I: Development of a binary direct relationship matrix. We obtained the binary direct relationship matrix (see Appendix 4(a)) by converting the diagonal entries of Appendix 3(a) into 0.

Step II: Establishment of a fuzzy direct relationship matrix. We employed fuzzy set theory to increase the sensitivity of analysis. Potential interactions between pairs of drivers can be qualitatively defined by linguistic variables on 0-1 scale, with 0 – indicating no influence, 0.1 – very low influence, 0.3 – low influence, 0.5 – medium influence, 0.7 – high influence, 0.9 – very high influence, and 1 – complete influence. The two professors involved in step III of the TISM analysis were asked to re-rate the relationships between drivers using these values. Based on their opinions, we superimposed these new values onto the binary direct relationship matrix to obtain the fuzzy direct relationship matrix (see Appendix 4(b)).

Step III: Generation of a fuzzy MICMAC stabilized matrix. We followed Kandasamy et al.'s (2007) method to conduct fuzzy matrix multiplication, which is a process for generalizing Boolean matrix multiplication. According to fuzzy set theory, when two fuzzy matrices are multiplied, the outcome is still a fuzzy matrix. The matrix was multiplied repeatedly until the driving and dependence power of each driver was constant. We used the following rule to conduct the multiplication process:

$$C = A, B = \max_k [(\min (a_{ik}, b_{kj}))], \text{ where } A = [a_{ik}] \text{ and } B = [b_{kj}]$$

Following this rule and using MATLAB to calculate the matrices, we obtained the fuzzy MICMAC stabilized matrix shown in Appendix 4(c). We then produced a scatter chart to portray each driver based on the sum of its driving and dependence power (see Figure 6).

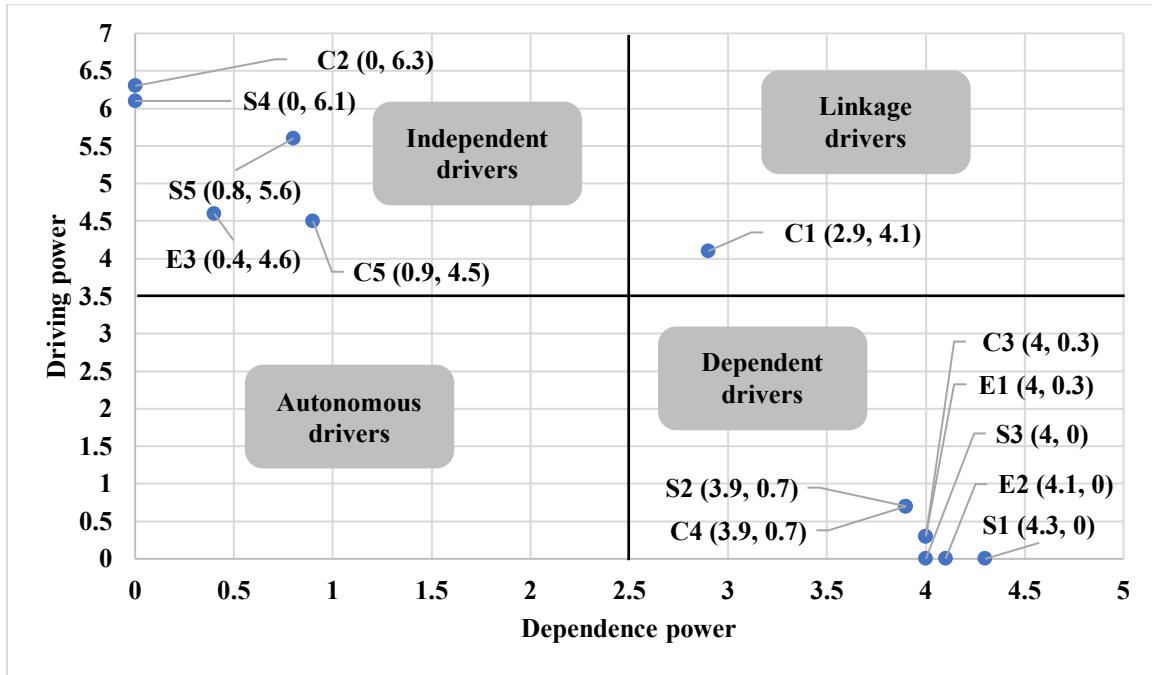


Figure 6. Fuzzy MICMAC analysis of drivers

Based on the fuzzy MICMAC analysis results, we clustered the 13 drivers into four categories: independent, linkage, autonomous, and dependent.

Independent drivers cluster: Drivers in this cluster are characterized by strong driving but weak dependence power. The five independent drivers are strengthening farmers' agri-tech skills training (S4), government subsidies for agricultural facilities (C2), reducing waste by controlling resource competition (E3), improving working conditions (S5), and accelerating circular agriculture (C5). These drivers can enable or enhance other drivers and act as the root cause of all drivers, thereby improving the performance of I4.0 technology deployment to achieve AFSC sustainability. Strengthening farmers' agri-tech skills training (S4) and government subsidies for agricultural facilities (C2) should be critically considered, as they have the highest driving power and are located at the lowest level of the TISM hierarchy. However, it is difficult to reskill and upskill farmers, because aging farmers may be reluctant to receive new knowledge. One interviewee stated: *"Most young people have gone out to work, leaving some 50 to 60, or even 70-year-olds who are still farming, and it is difficult for these people to accept new knowledge"*.

Dependent drivers cluster: Drivers in this cluster are characterized by strong dependence but weak driving power. Unlike independent drivers that mainly enable or enhance other drivers,

dependent drivers have the fewest opportunities to enable others. They are strongly dependent on other drivers for their achievement, and therefore appear at a relatively high level of the TISM hierarchy. The seven dependent drivers are reducing work intensity (S1), reducing human exposure to pesticides (S3), reducing groundwater pollution (E2), reducing carbon emissions (E1), improving product safety and farms' productivity (C3), reducing labor costs (C4), and reducing labor headcount (S2).

Linkage drivers cluster: Drivers in this cluster have relatively strong driving and dependence power and are characterized as unstable. They act as links between independent and dependent drivers. Therefore, any changes in the lower level of independent drivers may affect these drivers and further influence the higher level of dependent drivers. Only one linkage driver is identified in this study: enhancing the efficiency of water and fertilizer use (C1).

Autonomous drivers cluster: Drivers in this cluster are characterized by relatively weak driving and dependence power. They are considered to have few or even no connections with other drivers, and thus have little influence on the system. There are no autonomous drivers in this cluster, which means that all the drivers identified are effective for deploying I4.0 technologies to achieve AFSC sustainability.

7. Discussion

This study generates insights into the deployment of I4.0 technologies to achieve AFSC sustainability and address our three questions. First, we identify 13 drivers that facilitate I4.0 deployment to achieve AFSC sustainability, including some rarely mentioned in previous literature. Second, we prioritize the drivers by ranking the categories of drivers, drivers within each category, and their global ranking. Third, we generate models of drivers' interrelationships and categorizations, and thereby provide insights into which should be given critical attention.

Our study thus makes several contributions to existing knowledge. First, it contributes by identifying new drivers of I4.0 technology deployment to achieve sustainable AFSCs. For example, we find that reducing work intensity, reducing human exposure to pesticides, reducing groundwater pollution, and enhancing the efficiency of water and fertilizer use are

seldom mentioned in previous studies (see Table 2). However, other drivers are supported by the extant literature. Yadav et al. (2020) highlight that sustainable human resource management, continuous monitoring of emissions reductions, and green design and disposal systems are drivers of I4.0 technology deployment to achieve sustainability in manufacturing organizations. Our study confirms that the agri-food industry is adopting I4.0 technologies to reduce labor costs, headcount, and carbon emissions, and to reduce waste by controlling resource competition. Bhatia and Kumar (2022) find that improving the efficiency of the manufacturing process, product quality, consumption of resources, and information sharing are success factors for deploying I4.0 technologies in India's automobile industry. Our study supports their results by highlighting that enhancing the efficiency of water and fertilizer use and increasing product safety and farms' productivity are drivers of I4.0 deployment in China's agri-food industry. Rad et al. (2022) reveal that training and new competencies, top management support, and knowledge development are enablers of I4.0 technology deployment. Our study partially supports their results by confirming that AFSC stakeholders implement I4.0 technologies to strengthen their agri-tech skills. Srhir et al. (2023) highlight that I4.0 technologies can enhance various aspects of supply chain sustainability, including improved productivity and value creation opportunities on the economic dimension, better water management, efficient use of energy, and reduced carbon emissions on the environment dimension, and good working conditions on the social dimension. However, their study is a literature review, and therefore lacks industry-specific drivers. Our study confirms agri-food industry-specific drivers, including improving working conditions, enhancing the efficiency of water and fertilizer use, reducing groundwater pollution, and accelerating circular agriculture.

Second, our driver prioritization results also provide new understandings. For example, in Jamwal et al.'s (2021) study of a sustainability framework for I4.0, their prioritization results give the economic dimension the highest weighting, and the environmental dimension the lowest. Our study partially supports their results by highlighting that Chinese AFSC stakeholders are more concerned about the economic dimension of AFSC sustainability when deploying I4.0 technologies, followed by the environmental and social dimensions. Sharma et al.'s (2021) study of the impact of I4.0 adoption on sustainability shows that productivity, reduced emissions, and non-invasive interactions rank first on the economic, environmental, and social dimensions of sustainability, respectively. However, our results differ in prioritizing enhancing the efficiency of water and fertilizer use, reducing groundwater pollution, and reducing work intensity on the economic, environmental, and social dimensions of

sustainability, respectively. This contrast illustrates that various sustainability frameworks for I4.0 have been proposed because different countries have differing I4.0 strategies (e.g., China's Made in China 2025 and India's Digital India) and diverse cultural value orientations, and specific industries have unique characteristics.

Third, we identify that strengthening farmers' agri-tech skills training and government subsidies for agricultural facilities are two key drivers of I4.0 technology deployment to achieve AFSC sustainability. This finding differs from most existing studies. For example, Krishnan et al. (2021) propose that top management interest in implementing I4.0 is critical, Harikannan et al. (2021) suggest that societal pressure and public awareness are of prominent importance, and Kumar et al. (2022) state that environmental regulations for sustainability, adequate labor laws for less-skilled workforces in the digital environment, and continuous support and commitment from top management are key. Our study differs from these in considering specific characteristics of the Chinese agri-food industry. First, more than 60% of farmers in China are over the age of 45, and older individuals tend to be less receptive to new knowledge and skills. Second, national, provincial, and local governments have agri-tech extension and service centres that act as knowledge brokers between knowledge providers and agri-food industry practitioners. However, these exist in name only in many places. Third, with China's hierarchical value orientation, agri-food industry practitioners are expected to use intelligent agricultural equipment, so more subsidies are provided to those willing to do so. Accordingly, we conclude that simply receiving governmental support or subsidies is insufficient, and that reskilling or upskilling of agri-food industry practitioners is also necessary.

7.1 Theoretical contributions

Previous studies have integrated various theories to explore I4.0 adoption to achieve supply chain sustainability. The widely adopted theories include RBV, PBV, and DC. For example, Bag et al. (2021) adopt DC and PBV to understand why adopting I4.0 can facilitate sustainable supply chain management. Their results indicate that the mediating role of 10R (e.g., refuse, reuse, rethink, and repurpose) principles generate positive impacts on sustainable supply chain performance. Belhadi et al. (2022) combine DC and PBV to understand how I4.0 enabled practices can help to achieve sustainable supply chains. They conclude that the adoption of I4.0 enables digital business transformation (DBS), organizational ambidexterity (OA), and circular business models (CBM), and therefore contributing to supply chain's sustainable performance.

Erboz et al. (2022) from the theoretical lens of RBV to understand the relationship between I4.0 adoption and sustainable supply chain performance and conclude that I4.0 adoption activates supply chain integration, and the latter contributes to supply chain sustainability. Appendix 5 shows empirical studies focusing on I4.0 enabled sustainable supply chains.

Despite previous studies have adopted various theories to explore the topic, most of them concentrate on the post-I4.0 adoption conditions to examine the mediating roles of mechanisms or capabilities can be used to leverage supply chain sustainability, such as Umar et al. (2022) explore I4.0-enabled green sustainable supply chain practices on supply chain sustainability and Khan et al. (2023) investigate of how I4.0 adoption impacts social, environmental and economic performance of supply chain sustainability. Less understood is when I4.0 technologies can be successfully adopted and therefore help to tackle sustainability challenges and achieve supply chain sustainability. Our study is different from most of the previous studies and acts as the initial step to shed light on pre-I4.0 adoption conditions, and highlight the social, economic and environmental forces that can be used to enable I4.0 adoption. Therefore, this study contributes to MRT by highlighting mechanisms (adoption of I4.0 technologies) + contexts (social, economic, and environmental forces) = achievement of AFSC sustainability (see Figure 7). Other studies (e.g., Bag et al. 2021; Erboz et al. 2022; Strandhagen et al. 2022; Khan et al. 2023; Margherita and Braccini, 2023) consider that the adoption of I4.0 can be used as a mechanism and posit some general contexts (e.g., manufacturing, shipping building, textile and agri-food) that can be used, but they fail to highlight specific contexts to achieve supply chain sustainability. However, we still find several studies that can adopt the framework of mechanisms + context = outcomes. For example, under the context of lean and sustainable manufacturing, the ambidextrous innovation capabilities generated by the context can facilitate I4.0 adoption, and further contributes to the development of sustainable supply chains (Dixit et al. 2022). Under coercive, normative, and mimetic pressures, the exploration and exploitation orientations can be facilitated and therefore helps to adopt I4.0 technologies (Gupta et al. 2020). Moreover, this study also indicates that strengthening farmer's agri-tech skills training and government subsidies for agricultural facilities are two key context forces in enabling I4.0 technologies.

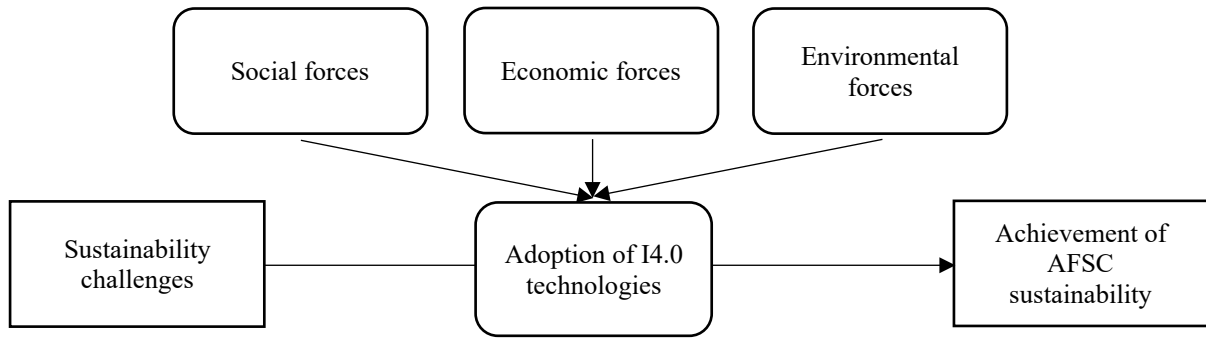


Figure 6. Evaluated conceptual framework of 14.0 technology adoption

7.2 Implications for AFSC practice

This study has two key implications for practice. First, the drivers and the prioritization framework can be used by AFSC practitioners to better understand the benefits of I4.0 technology deployment. For example, it has positive effects on reducing groundwater pollution and carbon emissions, reducing work intensity and human exposure to pesticides, enhancing water and fertilizer use and reducing labor costs. This is critical for AFSC practitioners to understand because China has promised to achieve peak carbon emissions before 2030 and fight climate change. Thus, these results should be widely disseminated across policymakers, AFSC practitioners, research institutes, and wider society to generate broad impacts. Second, governments should focus on agri-tech skills training and providing subsidies to accelerate applications of I4.0 technologies. Chinese AFSC practitioners might gain knowledge and skills from agricultural equipment manufacturers and agricultural research institutes, but most practitioners do not trust these bodies, believing that they lack experience. Thus, knowledge brokers, and especially non-profit knowledge brokers, should be established to work to improve sharing of knowledge and skills. For example, the Chinese government should make national, provincial, and local agri-tech extension and service centres work more effectively to share knowledge and skills with AFSC practitioners. Regarding subsidies, these are currently only given to agricultural equipment manufacturers. Governments should also consider paying subsidies to knowledge brokers, based on performance indicators such as the number of educated AFSC practitioners.

7.3 Limitations and future research directions

As with all research, there are limitations, which should be acknowledged. First, as we collected data specific to the agri-food industry in China, it limits generalizability of the results. Future studies might use large-scale surveys to collect data from other countries or regions that are also actively pursuing I4.0 technologies, thereby enabling cross-cultural comparisons and a broader understanding of the drivers. Second, this study does not distinguish between different agri-food industry contexts (e.g., meat processing, canned food processing), thus limiting a deeper understanding of a specific context. Future studies should encompass a wider range of agri-food industry contexts, such as collecting data from a range of agri-food industry practitioners focusing on crops, livestock, and fisheries to gain a more comprehensive understanding of how I4.0 technologies impact on various sectors within the agri-food industry. Third, in this study we used two MCDM techniques (fuzzy AHP and fuzzy-TISM-MICMAC) to analyze our drivers, but the results are not definitive. Other MCDM techniques might be applied to enrich and deepen understanding, such as the best-worst method to determine the most and least desirable drivers or DEMATEL to analyze cause-effect relationships between the drivers or Vle Kriterijumsko KOMPromisno Rangiranje (VIKOR) to rank and select from a set of drivers. Combining two or more MCDM techniques is useful for balancing the shortcomings of any single method, validating the findings, and providing a more robust understanding of the relative importance of drivers (Velasquez and Hester. 2013). Fourth, as we used a cross-sectional survey based on data collected from November 2021 to March 2022, it limits understanding of the rapidly evolving nature of I4.0. Future research might adopt a longitudinal approach to capture the evolving nature of I4.0 technology adoption in AFSCs.

8. Conclusion

This study was motivated to identify and understand the drivers of I4.0 deployment that are unique to the agri-food industry and how I4.0 can contribute to the sustainability of AFSC. Using several quantitative analytical techniques, these drivers were weighted based on the environmental, economic, and social dimensions of AFSC sustainability. A conceptual framework was developed to provide AFSC practitioners with a holistic understanding of I4.0 technology deployment across the three dimensions of AFSC sustainability. The results also have implications for AFSC researchers as we make a call to action for future research to focus on AFSC sustainability across regions. Specifically in the context of developing countries as

there is a stubbornly low number of studies that are being published from a Southern perspective, as such studies can inform national and international interventions to achieve sustainability.

Declarations:

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

Data will be made available on request

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Funding

Not applicable

Authors' contributions

Zhao, G: Writing – review & editing, writing – original draft, methodology, investigation, formal analysis, conceptualization. **Chen, X:** Writing – review & editing. **Jones, P:** Writing – review & editing. **Liu, S:** Writing – review & editing. **Lopez, C:** Writing – review & editing. **Leoni, L:** Writing – review & editing. **Dennehy, D:** Writing – review & editing.

Acknowledgements

Not applicable

References:

Abdul-Hamid, A-Q., Ali, M.H., Osman, L.H., Tseng, M-L. (2021). The drivers of industry 4.0 in a circular economy: The palm oil industry in Malaysia. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2021.129216>

- Agrawal, R., Wankhede, V.A., Kumar, A., Luthra, S., & Huisingh, D. (2022). Progress and trends in integrating industry 4.0 within circular economy: A comprehensive literature review and future research propositions. *Business Strategy and the Environment*, 31(1), 559-579.
- Alahakoon, D., Nawaratne, R., Xu, Y., Silva, D.D., Sivarajah, U., & Gupta, B. (2023). Self-building artificial intelligence and machine learning to empower big data analytics in smart cities. *Information Systems Frontiers*, 25, 221-240.
- Alguliyev, R., Imamverdiyev, Y., & Sukhostat, L. (2018). Cyber-physical systems and their security issues. *Computers in Industry*, 100, 212-223.
- Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L., & Menesatti, P. (2019). A review on blockchain applications in the agri-food sector. *Journal of the Science of Food and Agriculture*, 99(14), 6129-6138.
- Aoun, A., Ilinca, A., Ghandour, M., & Ibrahim, H. (2021). A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. *Computers & Industrial Engineering*, <https://doi.org/10.1016/j.cie.2021.107746>
- Awan, U., Sroufe, R., & Shahbaz, M. (2021). Industry 4.0 and the circular economy: a literature review and recommendations for future research. *Business Strategy and the Environment*, 30(4), 2038-2060.
- Awasthi, A., Govindan, K., & Gold, S. (2018). Multi-tier sustainable global supplier selection using a fuzzy AHP-VIKOR based approach. *International Journal of Production Economics*, 195, 106-117.
- Bag, S., Gupta, S., Kumar, S. (2021). Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *International Journal of Production Economics*, <https://doi.org/10.1016/j.ijpe.2020.107844>
- Barriball, K.L., & While, A. (1994). Collecting data using semi-structured interview: A discussion paper. *Journal of Advanced Nursing*, 19, 328-335.
- Belaud, J-P., Prioux, N., Vialle, C., & Sablayrolles, C. (2019). Big data for agri-food 4.0: application to sustainability management for by-products supply chain. *Computers in Industry*, 111, 41-50.
- Belhadi, A., Kamble, S., Gunasekaran, A., Mani, V. (2022). Analyzing the mediating role of organizational ambidexterity and digital business transformation on industry 4.0 capabilities and sustainable supply chain performance. *Supply Chain Management: An International Journal*, 27(6), 696-711.

- Bhatia, M.S., & Kumar, S. (2022). Critical success factors of industry 4.0 in automotive manufacturing industry. *IEEE Transactions on Engineering Management*, 69(5), 2439-2435.
- Bhosale, V.A., & Kant, R. (2016). An integrated ISM fuzzy MICMAC approach for modelling the supply chain knowledge flow enablers. *International Journal of Production Research*, 54(24), 7374-7399.
- Birkel, H., & Muller, J.M. (2021). Potentials of industry 4.0 for supply chain management within the triple bottom line of sustainability – A systematic literature review. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2020.125612>
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3, 77-101.
- Buckley, J.J. (1985). Fuzzy hierarchical analysis. *Fuzzy Sets and Systems*, 17(3), 233-247.
- Burgess, R.G. (1984). *In the field: An introduction to field research*. London: Unwin Hyman.
- Burns, A.J., Roberts, T.L., Posey, C., Lowry, P.B., Fuller, B. 2023. Going beyond deterrence: a middle-range theory of motives and controls for insider computer abuse. *Information Systems Research* 34(1), pp. 342-362.
- CABS. (2021). *Academic Journal Guide 2021*. London: Chartered Association of Business Schools.
- Chai, J.J.K., O’Sullivan, C., Gowen, A.A., Rooney, B., & Xu, J-L. (2022). Augmented/mixed reality technologies for food: A review. *Trends in Food Science & Technology*, 124, 182-194.
- Chatterjee, S., Chaudhuri, R., Kamble, S., Gupta, S., & Sivarajah, U. (2023). Adopting of artificial intelligence and cutting-edge technologies for production system sustainability: a moderator-mediation analysis. *Information Systems Frontiers*, 25, 1779-1794.
- Chauhan, C., Sharma, A., & Singh, A. (2021). A SAP-LAP linkages framework for integrating Industry 4.0 and circular economy. *Benchmarking: An International Journal*, 28(5), 1638-1664.
- Chou, Y-C., & Shao, B.B.M. (2023). An empirical study of information technology capabilities to enable value chain activities and interfaces. *Information Systems Frontiers*, 25, 1533-1547.
- CPC News. (2022). Shandong: Insert the wings of science and technology into agriculture to help stabilize China’s grain. *CPC News*, June 10.

- Craighead, C.W., Cheng, L., Ketchen Jr, D.J. 2024. Using middle-range theorizing to advance supply chain management research: a how-to primer and demonstration. *Journal of Business Logistics* 45: e12381.
- Creswell, J.W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*, 4th ed. Thousand Oaks, CA: Sage Publications.
- Dadhaneeya, H., Nema, P.K., & Arora, V.K. (2023). Internet of things in food processing and its potential in Industry 4.0 era: a review. *Trends in Food Science & Technology*, <https://doi.org/10.1016/j.tifs.2023.07.006>
- Dankar, I., Haddarah, A., Omar, F.E.L., Sepulcre, F., & Pujola, M. (2018). 3D printing technology: The new era for food customization and elaboration. *Trends in Food Science & Technology*, 75, 231-242.
- De Carvalho, M.I., Relvas, S., & Barbosa-Povoa, A.P. (2022). A roadmap for sustainability performance assessment in the context of agri-food supply chain. *Sustainable Production and Consumption*, 34, 565-585.
- De Sousa Jabbour, A.B.L., Jabbour, C.J.C., Choi, T-M., Latan, H. (2022). Better together: evidence on the joint adoption of circular economy and industry 4.0 technologies. *International Journal of Production Economics*, <https://doi.org/10.1016/j.ijpe.2022.108581>
- Dixit, A., Jakhar, S.K., Kumar, P. (2022). Does lean and sustainable manufacturing lead to Industry 4.0 adoption: the mediating role of ambidextrous innovation capabilities. *Technological Forecasting & Social Change*, <https://doi.org/10.1016/j.techfore.2021.121328>
- Dora, M., Kumar, A., Mangla, S.K., Pant, A., & Kamal, M.M. (2022). Critical success factors influencing artificial intelligence adoption in food supply chains. *International Journal of Production Research*, 60(14), 4621-4640.
- Duong, L.N.K., Al-Fadhli, M., Jagtap, S., Bader, F., Martindale, W., Swainson, M., & Paoli, A. (2020). A review of robotics and autonomous systems in the food industry: From the supply chain perspective. *Trends in Food Science & Technology*, 106, 355-364.
- Enrique, D.V., Marodin, G.A., Santos, F.B.C., & Frank, A.G. (2023). Implementing industry 4.0 for flexibility, quality, and productivity improvement: technology arrangements for different purposes. *International Journal of Production Research*, 61(20), 7001-7026.
- Erboz, G., Huseyinoglu, I.O.Y., Szegedi, Z. (2022). The partial mediating role of supply chain integration between Industry 4.0 and supply chain performance. *Supply Chain Management: An International Journal*, 27(4), 538-559.

- Erevelles, S., Fukawa, N., & Swayne, L. (2016). Big data consumer analytics and the transformation of marketing. *Journal of Business Research*, 69(2), 897-904.
- Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., & Strandhagen, J.O. (2022). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research*, 308, 125-143.
- Gebhardt, M., Kopyto, M., Birkel, H., & Hartmann, E. (2022). Industry 4.0 technologies as enablers of collaboration in circular supply chains: A systematic literature review. *International Journal of Production Research*, 60(23), 6967-6995.
- Ghobakhloo, M. (2020). Industry 4.0, digitalization, and opportunities for sustainability. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2019.119869>
- Gupta, S., Modgil, S., Gunasekaran, A., Bag, S. (2020). Dynamic capabilities and institutional theories for Industry 4.0 and digital supply chain. *Supply Chain Forum: An International Journal*, 21(3), 139-157.
- Gupta, S., Modgil, S., Lee, C-K., & Sivarajah, U. (2023). The future is yesterday: use of AI-driven facial recognition to enhance value in the travel and tourism industry. *Information Systems Frontiers*, 25, 1179-1195.
- Harikannan, N., Vinodh, S., & Gurumurthy, A. (2021). Sustainable industry 4.0 – An exploratory study for uncovering the drivers for integration. *Journal of Modelling in Management*, 16(1), 357-376.
- Hassan, N., Lowry, P.B. 2015. Seeking middle-range theories in information systems research. *International Conference on Information Systems (ICIS 2015)*, Fort Worth, December 13-18.
- Huang, C-H., Chen, P-J., Chen, B-W., & Zheng, J-X. (2021). A robot-based intelligent management design for agricultural cyber-physical systems. *Computers and Electronics in Agriculture*, <https://doi.org/10.1016/j.compag.2020.105967>
- Huber, R., Oberlander, A.M., Faisst, U., & Roglinger, M. (2022). Disentangling capabilities for industry 4.0 – An information systems capability perspective. *Information Systems Frontiers*, <https://doi.org/10.1007/s10796-022-10260-x>
- Jamwal, A., Agrawal, R., Sharma, M., Kumar, V., & Kumar, S. (2021). Developing a sustainability framework for industry 4.0. *Procedia CIRP*, 98, 430-435.
- Javaid, M., Haleem, A., Singh, R.P., & Suman, R. (2022). Enhancing smart farming through the applications of agriculture 4.0 technologies. *International Journal of Intelligent Networks*, 3, 150-164.

- Jena, J., Sidharth, S., Thakur, L.S., Pathak, D.K., & Pandey, V.C. (2017). Total interpretive structural modeling (TISM): Approach and application. *Journal of Advances in Management Research*, 14(2), 162-181.
- Jogulu, U.D., & Pansiri, J. 2011. Mixed methods: A research design for management doctoral dissertations. *Management Research Review*, 34(6), 687-701.
- Kamienski, C., Soinenen, J-P., Taumberger, M., Dantas, R., Toscano, A., Cinotti, T.S., Maia, R.F., & Neto, A.T. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*, 19, 276.
- Karmaker, C.L., Aziz, R.A., Ahmed, T., Misbauddin, S.M., Moktadir, M.A. (2023). Impact of Industry 4.0 technologies on sustainable supply chain performance: The mediating role of green supply chain management practices and circular economy. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2023.138249>
- Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N., & Lafci, C. (2022). Analyzing the drivers of smart sustainable circular supply chain for sustainable development goals through stakeholder theory. *Business Strategy and the Environment*, 31(7), 335-3353.
- Kandasamy, W.B.V., Smarandache, F., & Ilanthenral, K. (2007). *Elementary fuzzy matrix theory and fuzzy models for social scientists*. Los Angeles, CA: Automaton.
- Khan, S.A.R., Tabish, M., Zhang, Y. (2023). Embrace of industry 4.0 and sustainable supply chain practices under the shadow of practice-based view theory: ensuring environmental sustainability in corporate sector. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2023.136609>
- King, N. 2004. Using templates in the thematic analysis of text. In C. Cassell and G. Symon (Eds), *Essential guide to qualitative methods in organizational research* (pp. 257-270). London: Sage.
- King, N., & Horrocks, C. (2010). *Interviews in qualitative research*. London: Sage.
- Koh, L., Orzes, G., & Jia, F. (2019). The fourth industrial revolution (industry4.0): Technologies disruption on operations and supply chain management. *International Journal of Operations & Production Management*, 39(6/7/8), 817-828.
- Krishnan, S., Gupta, S., Kaliyan, M., Kumar, V., & Garza-Reyes, J.A. (2021). Assessing the key enablers for industry 4.0 adoption using MICMAC analysis: A case study. *International Journal of Productivity and Performance Management*, 70(5), 1049-1071.
- Kumar, A., Choudhary, S., Garza-Reyes, J.A., Kumar, V., Khan, S.A.R., & Mishra, N. (2021). Analysis of critical success factors for implementing industry 4.0 integrated circular supply

- chain – Moving towards sustainable operations. *Production Planning & Control*, <https://doi.org/10.1080/09537287.2021.1980905>
- Kumar, D., & Rahman, Z. (2017). Analyzing enablers of sustainable supply chain: ISM and fuzzy AHP approach. *Journal of Modeling in Management*, 12(3), 498-524.
- Kumar, V., Vrat, P., & Shankar, R. (2022). Factors influencing the implementation of industry 4.0 for sustainability in manufacturing. *Global Journal of Flexible Systems Management*, 23(4), 453-478.
- Lee, A.S., & Baskerville, R.L. (2012). Conceptualizing generalizability: new contributions and a reply. *MIS Quarterly*, 36(3), 749-761.
- Lee, E.S., & Li, R.L. (1988). Comparison of fuzzy numbers based on the probability measure of fuzzy events. *Computational Mathematics and Application*, 15(10), 887-896.
- Liu, Y., Eckert, C.M., & Earl, C. (2020). A review of fuzzy AHP methods for decision-making with subjective judgements. *Expert Systems with Applications*, 161, <https://doi.org/10.1016/j.eswa.2020.113738>
- Liu, Z., Zhang, M., Bhandari, B., & Wang, Y. (2017). 3D printing: printing precision and application in food sector. *Trends in Food Science & Technology*, 69, 83-94.
- Lu, H., Zhao, G., & Liu, S. (2022). Integrating circular economy and industry 4.0 for sustainable supply chain management: A dynamic capability view. *Production Planning & Control*, <https://doi.org/10.1080/09537287.2022.2063198>
- Luthra, S., Kumar, A., Zavadskas, E.K., Mangla, S.K., & Garza-Reyes, J. (2020). Industry 4.0 as an enabler of sustainability diffusion in supply chain: An analysis of influential strength of drivers in an emerging economy. *International Journal of Production Research*, 58(5), 1505-1521.
- Luthra, S., & Mangla, S.K. (2018). When strategies matter: Adoption of sustainable supply chain management practices in an emerging economy's context. *Resources, Conservation and Recycling*, 138, 194-206.
- Mahdad, M., Hasanov, M., Isakhanyan, G., & Dolfisma, W. (2022). A smart web of firms, farms and internet of things (IOT): Enabling collaboration-based business models in the agri-food industry. *British Food Journal*, 124(6), 1857-1874.
- Mangla, S.K., Luthra, S., Rich, N., Kumar, D., Rana, N.P., & Dwivedi, Y.K. (2018). Enablers to implement sustainable initiatives in agri-food supply chains. *International Journal of Production Economics*, 203, 379-393.

- Mardani, A., Zavadskas, E.K., Streimikene, D., Jusoh, A., & Khoshnoudi, M. (2017). A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. *Renewable and Sustainable Energy Reviews*, 70, 1298-1322.
- Margherita, E.G., & Braccini, A.M. (2023). Industry 4.0 technologies in flexible manufacturing for sustainable organizational value: reflections from a multiple case study of Italian manufacturers. *Information Systems Frontiers*, 25, 995-1016.
- Martins, C.L., & Pato, M.V. (2019). Supply chain sustainability: A tertiary literature review. *Journal of Cleaner Production*, 225, 995-1016.
- Mastrocinque, E., Ramirez, F.J., Honrubia-Escribano, A., & Pham, D.T. (2022). Industry 4.0 enabling sustainable supply chain development in the renewable energy sector: A multi-criteria intelligent approach. *Technological Forecasting & Social Change*, <https://doi.org/10.1016/j.techfore.2022.121813>
- McIntosh, M.J., & Morse, J.M. (2015). Situating and constructing diversity in semi-structured interviews. *Global Qualitative Nursing Research*, 2, 1-12.
- Mesquita, L.L., Lizarelli, F.L., Duarte, S., & Oprime, P.C. (2022). Exploring relationships for integrating lean, environmental sustainability and industry 4.0. *International Journal of Lean Six Sigma*, 13(4), 863-896.
- Ministry of Agriculture and Rural Affairs of the People's Republic of China. (2021). Shandong's total agriculture output value breaks one trillion yuan. Shandong Agricultural Information Network, February 5, http://www.moa.gov.cn/xw/qg/202102/t20210205_6361286.htm
- Ministry of Science and Technology. (2022). *Science and technology supported carbon peak and carbon neutrality implementation plan 2022 – 2030*. Beijing: Ministry of Science and Technology, <http://www.gov.cn/zhengce/zhengceku/2022-08/18/5705865/files/94318119b8464e2583a3d4284df9c855.pdf>
- Mithas, S., Chen, Z-L., Saldanha, T.J.V., & Silveira, A.D.O. (2022). How will artificial intelligence and industry 4.0 emerging technologies transform operations management? *Production and Operations Management*, 31(12), 4475-4487.
- Mota, R.O., Filho, M.G., Osiro, L., Ganga, G.M.D., & Mendes, G.H.S. (2021). Unveiling the relationship between drivers and capabilities for reduced time-to-market in start-ups: A multi-method approach. *International Journal of Production Economics*, <https://doi.org/10.1016/j.ijpe.2020.108018>
- Naseem, M.H., & Yang, J. (2021). Role of Industry 4.0 in supply chains sustainability: a systematic literature review. *Sustainability*, 13, 9544.

- Nowell, L.S., Norris, J.M., White, D.E., & Moules, N.J. (2017). Thematic analysis: Striving to meet the trustworthiness criteria. *International Journal of Qualitative Methods* 16, 1-13.
- Pawson, R., Tilley, N. (1997). *Realistic Evaluation*. London, Sage.
- Pele, P., Schulze, J., Piramuthu, S., & Zhou, W. (2023). IoT and blockchain based framework for logistics in food supply chains. *Information Systems Frontiers*, 25, 1743-1756.
- Pellathy, D.A., In, J., Mollenkopf, D.A., Stank, T.P. (2018). Middle-range theorizing on logistics customer service. *International Journal of Physical Distribution & Logistics Management*, 48(1), 2-18.
- Petit, O., Javornik, A., & Velasco, C. (2022). We eat first with our (digital) eyes: Enhancing mental simulation of eating experiences via visual-enabling technologies. *Journal of Retailing*, 98(2), 277-293.
- Piccarozzi, M., Silvestri, C., Aquilani, B., & Silvestri, L. (2022). Is this a new story of the two giants? A systematic literature review of the relationship between industry 4.0, sustainability and its pillars. *Technological Forecasting & Social Change*, <https://doi.org/10.1016/j.techfore.2022.121511>
- Porter, K. (2015). 3D opportunity serves it up: Additive manufacturing and food. *Deloitte Insights*, June 19, <https://www2.deloitte.com/us/en/insights/focus/3d-opportunity/3d-printing-in-the-food-industry.html>
- Qin, J., Liu, Y., & Grosvenor, R. (2016). A categorical framework of manufacturing for industry 4.0 and beyond. *Procedia CIRP*, 52, 173-178.
- Rad, F.F., Oghazi, P., Palmie, M., Chirumalla, K., Pashkevich, N., Patel, P.C., & Sattari, S. (2022). Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies. *Industrial Marketing Management*, <https://doi.org/10.1016/j.indmarman.2022.06.009>
- Ranjha, A., Kaddoum, G., & Dev, K. (2022). Facilitating URLLC in UAV-assisted relay systems with multiple-mobile robots for 6G networks: a prospective of agriculture 4.0. *IEEE Transactions on Industrial Informatics*, 18(7), 4954-4965.
- Rejeb, A., Abdollahi, A., Rejeb, K., & Treiblmaier, H. (2022a). Drones in agriculture: A review and bibliometric analysis. *Computers and Electronics in Agriculture*, <https://doi.org/10.1016/j.compag.2022.107017>
- Rejeb, A., Keogh, J.G., & Rejeb, K. (2022b). Big data in the food supply chain: A literature review. *Journal of Data, Information and Management*, 4, 33-47.

- Ren, G., Lin, T., Ying, Y., Chowdhary, G., & Ting, K.C. (2020). Agricultural robotics research applicable to poultry production: A review. *Computers and Electronics in Agriculture*, <https://doi.org/10.1016/j.compag.2020.105216>
- Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*, 5th ed. Essex, England: Pearson Education Limited.
- Schwartz, S.H. (2006). A theory of cultural value orientations explication and applications. *Comparative Sociology*, 5(2-3), 137-182.
- Sengupta, T., Narayanamurthy, G., Moser, R., Pereira, V., & Bhattacharjee, D. (2022). Disruptive technologies for achieving supply chain resilience in COVID-19 era: an implementation case study of satellite and blockchain technologies in fish supply chain. *Information Systems Frontiers*, 24, 1107-1123.
- SDWF. (2023). *Pesticides and water pollution*. Saskatoon, SK: Safe Drinking Water Foundation, <https://www.safewater.org/fact-sheets-1/2017/1/23/pesticides>
- Seuring, S., & Muller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 16(15), 1699-1710.
- Sharma, R., Kamble, S.S., Gunasekaran, A., Kumar, V., & Kumar, A. (2020). A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. *Computers & Operations Research*, <https://doi.org/10.1016/j.cor.2020.104926>
- Sharma, M., Kamble, S., Mani, V., Sehrawat, R., Belhadi, A., & Sharma, V. (2021). Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2020.125013>
- Sharma, R., Kamble, S., Mani, V., Belhadi, A. (2022). An empirical investigation of the influence of Industry 4.0 technology capabilities on agriculture supply chain integration and sustainable performance. *IEEE Transactions on Engineering Management*, [10.1109/TEM.2022.3192537](https://doi.org/10.1109/TEM.2022.3192537)
- Si, S-L., You, X-Y., Liu, H-C., & Zhang, P. (2018). DEMATEL technique: a systematic review of the state-of-the-art literature on methodologies and applications. *Mathematical Problems in Engineering*, <https://doi.org/10.1155/2018/3696457>
- Sonar, H., Ghosh, S., Singh, R.K., Khanzode, V., Akarte, M., & Ghag, N. (2022). Implementing additive manufacturing for sustainability in operations: Analysis of enabling factors. *IEEE Transactions on Engineering Management*, <https://doi.org/10.1109/TEM.2022.3206234>

- Song, Y., Xue, D., Ma, B., Xia, S., Ye, H. 2023. Farming in arid areas depletes China's water. *Science* 379(6633), 651.
- Springmann, M., Clark, M., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519-525.
- Srhir, S., Jaegler, A., & Montoya-Torres, J.R. (2023). Uncovering industry 4.0 technology attributes in sustainable supply chain 4.0: A systematic literature review. *Business Strategy and the Environment*, <https://doi.org/10.1002/bse.3358>
- Statista. (2024). Export value of agricultural products from China from 2005 to 2023 <https://www.statista.com/statistics/1200541/chinas-export-value-of-agricultural-products/>
- Statista. (2024). Agricultural trade in China - statistics & facts. <https://www.statista.com/topics/9277/agricultural-trade-in-china/#topicOverview>
- Stank, T.P., Pellathy, D.A., In, J., Mollenkopf, D.A., Bell, J.E. (2017). New frontiers in logistics research: theorizing at the middle range. *Journal of Business Logistics* 38(1), 6-17.
- Strandhagen, J.W., Buer, S-V., Semini, M., Alfnes, E., Strandhagen, J.O. (2022). Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain. *Production Planning & Control*, 33(9-10), 995-1010.
- Sushil. (2012). Interpreting the interpretive structural model. *Global Journal of Flexible Systems Management*, 13(2), 87-106.
- Spanaki, K., Karafili, E., and Despoudi, S. (2021). AI applications of data sharing in agriculture 4.0: A framework for role-based data access control. *International Journal of Information Management*, 59, 102350.
- Taddei, E., Sassanelli, C., Rosa, P., & Terzi, S. (2022). Circular supply chains in the era of industry 4.0: A systematic literature review. *Computers & Industrial Engineering*, <https://doi.org/10.1016/j.cie.2022.108268>
- Tang, C.S., & Veelenturf, L.P. (2019). The strategic role of logistics in the industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review*, 129, 1-11.
- Tang, Y.M., Chau, K.Y., Kuo, W.T., & Liu, X.X. (2023). IoT-based information system on cold-chain logistics service quality (ICCLSQ) management in logistics 4.0. *Information Systems Frontiers*, <https://doi.org/10.1007/s10796-023-10393-7>
- Tsang, E.W.K. 2014. Generalizing from research findings: the merits of case studies. *International Journal of Management Reviews*, 16, 369-383.

- Tseng, M-L., Tan, R.R., Chiu, A.S.F., Chien, C-F., & Kuo, T.C. (2018). Circular economy meets industry 4.0: can big data drive industrial symbiosis? *Resources, Conservation and Recycling*, 131, 146-147.
- Tsolakis, N.K., Keramydas, C.A., Toka, A.K., Aidonis, D.A., & Iakovou, E.T. (2014). Agrifood supply chain management: A comprehensive hierarchical decision-making framework and acritical taxonomy. *Biosystems Engineering*, 120, 47-64.
- Umar, M., Khan, S.A.R., Yusliza, M.Y., Ali, S., Yu, Z. (2022). Industry 4.0 and green supply chain practices: an empirical study. *International Journal of Productivity and Performance Management*, 71(3), 814-832.
- Velasquez, M., & Hester, P.T. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research*, 10(2), 56-66.
- Wynsberghe, R.V., & Khan, S. (2007). Redefining case study. *International Journal of Qualitative Methods*, 6(2), 80-94.
- Yadav, G., Kumar, A., Luthra, S., Garza-Reyes, J.A., Kumar, V., & Batista, L. (2020). A framework to achieve sustainability in manufacturing organizations of developing economies using industry 4.0 technologies' enablers. *Computers in Industry*, <https://doi.org/10.1016/j.compind.2020.103280>
- Yadav, V.S., Singh, A.R., Raut, R.D., Mangla, S.K., Luthra, S., & Kumar, A. (2022). Exploring the application of industry 4.0 technologies in the agri-food supply chain: A systematic literature review. *Computers & Industrial Engineering*, <https://doi.org/10.1016/j.cie.2022.108304>
- Yin, R.K. (2009). *Case study research: design and methods*, 4th eds. Thousand Oaks, CA: Sage.
- Yin, R.K. (2017). *Case study research and applications: design and methods*. Thousand Oaks, CA: Sage.
- Yin, Y., Stecke, K.E., & Li, D. (2018). The evolution of production systems from industry 2.0 through industry 4.0. *International Journal of Production Research*, 56(1-2), 848-861.
- Yu, Z., Khan, S.A.R., & Umar, M. (2022). Circular economy practices and industry 4.0 technologies: A strategic move of automobile industry. *Business Strategy and the Environment*, 31(3), 796-809.
- Zhang, A., Venkatesh, V.G., Wang, J.X., Mani, V., Wan, M., & Qu, T. (2021). Drivers of industry 4.0-enabled smart waste management in supply chain operations: A circular economy perspective in China. *Production Planning & Control*, <https://doi.org/10.1080/09537287.2021.1980909>

- Zhang, C., Chen, Y., Chen, H., & Chong, D. (2021). Industry 4.0 and its implementation: a review. *Information Systems Frontiers*, <https://doi.org/10.1007/s10796-021-10153-5>
- Zhang, H. (2023). *Five articles to ensure food security*. Available at: http://www.moa.gov.cn/ztl/2023yhwj/wjjd_29327/202302/t20230227_6421628.htm#:~:text=%E6%95%B0%E6%8D%AE%E6%98%BE%E7%A4%BA%EF%BC%8C%E6%88%91%E5%9B%BD%E5%86%9C%E4%B8%9A%E4%BB%8E%E4%B8%9A,%E4%BC%9A%E6%8C%81%E7%BB%AD%E5%BE%88%E9%95%BF%E6%97%B6%E9%97%B4%E3%80%82 [Accessed: 20/03/2024].
- Zhao, G., Liu, S., Lopez, C., Chen, H., Lu, H., Mangla, S.K., & Elgueta, S. (2020). Risk analysis of the agri-food supply chain: A multi-method approach. *International Journal of Production Research*, 58(16), 4851-4876.
- Zhao, G., Liu, S., Lopez, C., Lu, H., Elgueta, S., Chen, H., & Boshkoska, B.M. (2019). Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions. *Computers in Industry*, 109, 83-99.
- Zhao, G., Liu, S., Wang, Y., Lopez, C., Ong, A., Chen, X. (2023). Reducing food waste from social innovation perspective: a review of measures, research gaps and future directions. *International Food and Agribusiness Management Review*, 26(2), 199-223.
- Zhao, G., Olan, F., Liu, S., Hormazabal, J.H., Lopez, C., Zubairu, N., Zhang, J., & Chen, X. (2022). Links between risk source identification and resilience capability building in agri-food supply chains: a comprehensive analysis. *IEEE Transactions on Engineering Management*, [10.1109/TEM.2022.3221361](https://doi.org/10.1109/TEM.2022.3221361)
- Zhao, G., Vazquez-Noguerol, M., Liu, S., & Parado-Prado, J.C. (2024). Agri-food supply chain resilience strategies for preparing, responding, recovering, and adapting in relation to unexpected crisis: a cross-country comparative analysis from the COVID-19 pandemic. *Journal of Business Logistics*, <https://doi.org/10.1111/jbl.12361>
- Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of industry 4.0 technologies in manufacturing context: A systematic literature review. *International Journal of Production Research*, 59(6), 1922-1954.
- Zissis, D., Aktas, E., & Bourlakis, M. (2017). A new process model for urban transport of food in the UK. *Transportation Research Procedia*, 22, 588-597.

Appendix 1 Fuzzy linguistic scales

Linguistic scale	Fuzzy number	Triangular fuzzy numbers	Triangular fuzzy reciprocal numbers
Equally important	$\tilde{1}$	(1,1,1)	(1,1,1)
Weakly important	$\tilde{3}$	(2,3,4)	(1/4,1/3,1/2)
Essentially important	$\tilde{5}$	(4,5,6)	(1/6,1/5,1/4)
Very strongly important	$\tilde{7}$	(6,7,8)	(1/8,1/7,1/6)
Absolutely important	$\tilde{9}$	(9,9,9)	(1/9,1/9,1/9)

Appendix 2 Initial and final reachability matrices

(a) Initial reachability matrix of drivers

Drivers	S1	S2	S3	S4	S5	E1	E2	E3	C1	C2	C3	C4	C5
S1	1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	1	0	0	0	0	0	0	0	0	1	1	0
S3	0	0	1	0	0	0	0	0	0	0	0	0	0
S4	1	1	1	1	1	1	1	1	1	0	1	1	1
S5	1	1	0	0	1	1	1	0	1	0	1	1	0
E1	1	0	0	0	0	1	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	1	0	0	0	0	0	0
E3	0	0	0	0	0	1	1	1	1	0	0	0	1
C1	1	1	1	0	0	1	1	0	1	0	1	1	0
C2	1	1	1	0	1	1	1	1	1	1	1	1	1
C3	0	0	0	0	0	0	1	0	0	0	1	0	0
C4	0	1	0	0	0	0	0	0	0	0	0	1	0
C5	1	1	1	0	1	1	1	0	1	0	1	1	1

(b) Final reachability matrix of drivers

Drivers	S1	S2	S3	S4	S5	E1	E2	E3	C1	C2	C3	C4	C5
S1	1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	1	0	0	0	0	1*	0	0	0	1	1	0
S3	0	0	1	0	0	0	0	0	0	0	0	0	0
S4	1	1	1	1	1	1	1	1	1	0	1	1	1
S5	1	1	1*	0	1	1	1	1*	1	0	1	1	1*
E1	1	0	0	0	0	1	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	1	0	0	0	0	0	0
E3	1*	1*	1*	0	1*	1	1	1	1	0	1*	1*	1
C1	1	1	1	0	0	1	1	0	1	0	1	1	0
C2	1	1	1	0	1	1	1	1	1	1	1	1	1
C3	0	0	0	0	0	0	1	0	0	0	1	0	0
C4	0	1	0	0	0	0	1*	0	0	0	1*	1	0
C5	1	1	1	0	1	1	1	1*	1	0	1	1	1

Note: * represents transitivity

Appendix 3 Partitioning of the reachability matrix into different levels

Driver	Reachability set (RS)	Antecedent set (AS)	$RS \cap AS$	Level
				1

Iteration 1				
S1	S1	S1,S4,S5,E1,E3,C1,C2,C5	S1	I
S2	S2,E2,C3,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	
S3	S3	S3,S4,S5,E3,C1,C2,C5	S3	I
S4	S1,S2,S3,S4,S5,E1,E2,E3,C1,C3,C4,C5	S4	S4	
S5	S1,S2,S3,S5,E1,E2,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
E1	S1,E1	S4,S5,E1,E3,C1,C2,C5	E1	
E2	E2	S2,S4,S5,E2,E3,C1,C2,C3,C4,C5	E2	I
E3	S1,S2,S3,S5,E1,E2,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
C1	S1,S2,S3,E1,E2,C1,C3,C4	S4,S5,E3,C1,C2,C5	C1	
C2	S1,S2,S3,S5,E1,E2,E3,C1,C2,C3,C4,C5	C2	C2	
C3	E2,C3	S2,S4,S5,E3,C1,C2,C3,C4,C5	C3	
C4	S2,E2,C3,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	
C5	S1,S2,S3,S5,E1,E2,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
Iteration 2				
S2	S2,C3,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	
S4	S2,S4,S5,E1,E3,C1,C3,C4,C5	S4	S4	
S5	S2,S5,E1,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
E1	E1	S4,S5,E1,E3,C1,C2,C5	E1	II
E3	S2,S5,E1,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
C1	S2,E1,C1,C3,C4	S4,S5,E3,C1,C2,C5	C1	
C2	S2,S5,E1,E3,C1,C2,C3,C4,C5	C2	C2	
C3	C3	S2,S4,S5,E3,C1,C2,C3,C4,C5	C3	II
C4	S2,C3,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	
C5	S2,S5,E1,E3,C1,C3,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
Iteration 3				
S2	S2,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	III
S4	S2,S4,S5,E3,C1,C4,C5	S4	S4	
S5	S2,S5,E3,C1,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
E3	S2,S5,E3,C1,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
C1	S2,C1,C4	S4,S5,E3,C1,C2,C5	C1	
C2	S2,S5,E3,C1,C2,C4,C5	C2	C2	
C4	S2,C4	S2,S4,S5,E3,C1,C2,C4,C5	S2,C4	III
C5	S2,S5,E3,C1,C4,C5	S4,S5,E3,C2,C5	S5,E3,C5	
Iteration 4				
S4	S4,S5,E3,C1,C5	S4	S4	

S5	S5,E3,C1,C5	S4,S5,E3,C2,C5	S5,E3,C5	
E3	S5,E3,C1,C5	S4,S5,E3,C2,C5	S5,E3,C5	
C1	C1	S4,S5,E3,C1,C2,C5	C1	IV
C2	S5,E3,C1,C2,C5	C2	C2	
C5	S5,E3,C1,C5	S4,S5,E3,C2,C5	S5,E3,C5	
Iteration 5				
S4	S4,S5,E3,C5	S4	S4	
S5	S5,E3,C5	S4,S5,E3,C2,C5	S5,E3,C5	
E3	S5,E3,C5	S4,S5,E3,C2,C5	S5,E3,C5	
C2	S5,E3,C2,C5	C2	C2	
C5	S5,E3,C5	S4,S5,E3,C2,C5	S5,E3,C5	V
Iteration 6				
S4	S4,S5,E3	S4	S4	
S5	S5,E3	S4,S5,E3,C2	S5,E3	VI
E3	S5,E3	S4,S5,E3,C2	S5,E3	VI
C2	S5,E3,C2	C2	C2	
Iteration 7				
S4	S4	S4	S4	VII
C2	C2	C2	C2	VII

Appendix 4 Matrices to perform fuzzy MICMAC analysis

(a) Binary direct relationship matrix

Drivers	S1	S2	S3	S4	S5	E1	E2	E3	C1	C2	C3	C4	C5
S1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	1	1	0
S3	0	0	0	0	0	0	0	0	0	0	0	0	0
S4	1	1	1	0	1	1	1	1	1	0	1	1	1
S5	1	1	0	0	0	1	1	0	1	0	1	1	0
E1	1	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	1	1	0	1	0	0	0	1
C1	1	1	1	0	0	1	1	0	0	0	1	1	0
C2	1	1	1	0	1	1	1	1	1	0	1	1	1
C3	0	0	0	0	0	0	1	0	0	0	0	0	0
C4	0	1	0	0	0	0	0	0	0	0	0	0	0
C5	1	1	1	0	1	1	1	0	1	0	1	1	0

(b) Fuzzy direct relationship matrix

Drivers	S1	S2	S3	S4	S5	E1	E2	E3	C1	C2	C3	C4	C5
S1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0
S3	0	0	0	0	0	0	0	0	0	0	0	0	0

S4	0.7	0.5	0.7	0	0.3	0.9	0.3	0.1	0.7	0	0.7	0.3	0.3
S5	0.9	0.3	0	0	0	0.9	0.5	0	0.7	0	0.5	0.3	0
E1	0.3	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0.7	0.3	0	0.5	0	0	0	0.3
C1	0.5	0.5	0.7	0	0	0.5	0.7	0	0	0	0.7	0.3	0
C2	0.9	0.7	0.9	0	0.3	0.5	0.7	0.3	0.5	0	0.5	0.3	0.3
C3	0	0	0	0	0	0	0.3	0	0	0	0	0	0
C4	0	0.7	0	0	0	0	0	0	0	0	0	0	0
C5	0.1	0.3	0.1	0	0.1	0.5	0.1	0	0.5	0	0.9	0.3	0

(c) Fuzzy MICMAC stabilized matrix

Drivers	S1	S2	S3	S4	S5	E1	E2	E3	C1	C2	C3	C4	C5	Driving power
S1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0.7
S3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S4	0.7	0.5	0.7	0	0.3	0.9	0.7	0.1	0.7	0	0.7	0.5	0.3	6.1
S5	0.9	0.5	0.7	0	0	0.9	0.7	0	0.7	0	0.7	0.5	0	5.6
E1	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0.3
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0.5	0.5	0.5	0	0.1	0.7	0.5	0	0.5	0	0.5	0.5	0.3	4.6
C1	0.5	0.5	0.7	0	0	0.5	0.7	0	0	0	0.7	0.5	0	4.1
C2	0.9	0.7	0.9	0	0.3	0.5	0.7	0.3	0.5	0	0.5	0.7	0.3	6.3
C3	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0.3
C4	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0.7
C5	0.5	0.5	0.5	0	0.1	0.5	0.5	0	0.5	0	0.9	0.5	0	4.5
Dependence power	4.3	3.9	4	0	0.8	4	4.1	0.4	2.9	0	4	3.9	0.9	

Appendix 5 Empirical studies focus on I4.0 enabling sustainable supply chains

Author(s) (year)	Theory adopted	Enabling mechanisms	Enabling or research contexts	Major findings
Gupta et al. (2020)	DC and institutional theory	Not mentioned	Coercive pressure, normative pressure, and mimetic pressure (Manufacturing)	Coercive pressure moderates the relationship of exploration and exploitation orientation to the intentions of adopting I4.0
Bag et al. (2021)	DC and PBV	I4.0 adoption	Manufacturing	I4.0 adoption facilitates 10R principles, and therefore generating positive impacts on sustainable supply chain development
Belhadi et al. (2022)	DC and PBV	Digital business transformation (DBS), organizational ambidexterity (OA), and circular business models (CBM)	Manufacturing	DBS and OA are direct I4.0 enabled practices, and CBM are indirect I4.0 enabled practices
De Sousa Jabbour et al. (2022)	RBV and complementarity theory	Joint adoption of I4.0 and CBM	Not clear	Joint adoption of I4.0 and CBM have positive effects on the social perspective of sustainability
Dixit et al. (2022)	Theory of conservatism	Not mentioned	Lean manufacturing and sustainable manufacturing	Under the context of lean and sustainable manufacturing, ambidextrous innovation capabilities can facilitate I4.0 adoption
Erboz et al. (2022)	RBV	I4.0 adoption	Manufacturing	I4.0 adoption activates supply chain integration, and further improves supply chain sustainability performance
Sharma et al. (2022)	RBV and DC	I4.0 technology capabilities and supply chain integration	Agri-food	I4.0 technology capabilities and supply chain integration have direct and indirect positive effects on sustainable AFSC performance
Strandhagen et al. (2022)	RBV	I4.0 adoption	Shipping building	I4.0 can help to solve sustainability challenges, and further improve sustainable performance
Umar et al. (2022)	PBV	Green sustainable supply chain practices	Manufacturing	I4.0 enabled green sustainable supply chain practices has positive effects on supply chain sustainability
Khan et al. (2023)	PBV	I4.0 adoption	Textile	I4.0 adoption has direct positive effects on environmental and social performances, and

				has indirect positive effects on economic performance
Margherita and Braccini (2023)	IT value theory	I4.0 adoption	Manufacturing	I4.0 adoption can achieve sustainable organizational values, such as better work conditions, reduced resources usage, improved process performance, and new job positions